

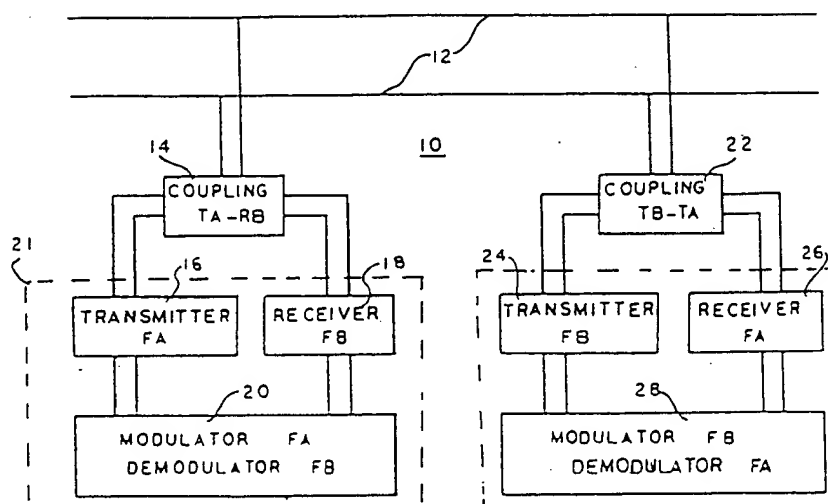


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DOC

(54) Title: POWER-LINE COMMUNICATION APPARATUS



(57) Abstract

Apparatus for power system communications includes a coupler (14) at each of two or more locations along a pair of power-lines, the coupler having a pair of serial LC circuits with an air coil. A transmitter (FA), a receiver (FB), and a modem (20) is also provided at each of the locations such that each of the LC circuits of the couplers (14) resonate at a given frequency. The apparatus incorporate novel non-linear transformers which eliminate the signal from the power line and its harmonics, and which permit rapid transmission of signals for communications and other uses.

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INTERNATIONAL SEARCH REPORT

International Application No

PCT/US90/02291

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all) ¹

According to International Patent Classification (IPC) or to both National Classification and IPC

IPC² H04B 1/50 H04L 5/14

U.S.CL. 370/30 340/310R

II. FIELDS SEARCHED

Minimum Documentation Searched ⁴Classification System ¹

Classification Symbols

U.S.CL. 370/24,27,28,30
340/310R,310ADocumentation Searched other than Minimum Documentation
to the extent that such Documents are Included in the Fields Searched ⁵III. DOCUMENTS CONSIDERED TO BE RELEVANT ^{1,6}

Category ⁷	Citation of Document, ^{1,6} with indication, where appropriate, of the relevant passages ^{1,7}	Relevant to Claim No. ^{1,8}
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Y	US, A, 4,058,678 (DUNN ET AL) 15 November 1977 See col. 6, line 32 - col. 11, line 3.	1,3,8-11,13-15, 17,18,24
A	US, A, 4,885,563 (JOHNSON ET AL) 05 December 1989	

⁹ Special categories of cited documents: ¹⁰¹¹ "A" document defining the general state of the art which is not considered to be of particular relevance¹² "E" earlier document but published on or after the international filing date¹³ "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)¹⁴ "O" document referring to an oral disclosure, use, exhibition or other means¹⁵ "P" document published prior to the international filing date but later than the priority date claimed¹⁶ "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention¹⁷ "X" document of particular relevance: the claimed invention cannot be considered novel or cannot be considered to involve an inventive step¹⁸ "Y" document of particular relevance: the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.¹⁹ "&" document member of the same patent family

IV. CERTIFICATION

Date of the Actual Completion of the International Search ²

17 OCTOBER 1990

International Searching Authority ³

ISA/US

Date of Mailing of this International Search Report ²

05 FEB 1991

Signature of Authorized Officer ⁴

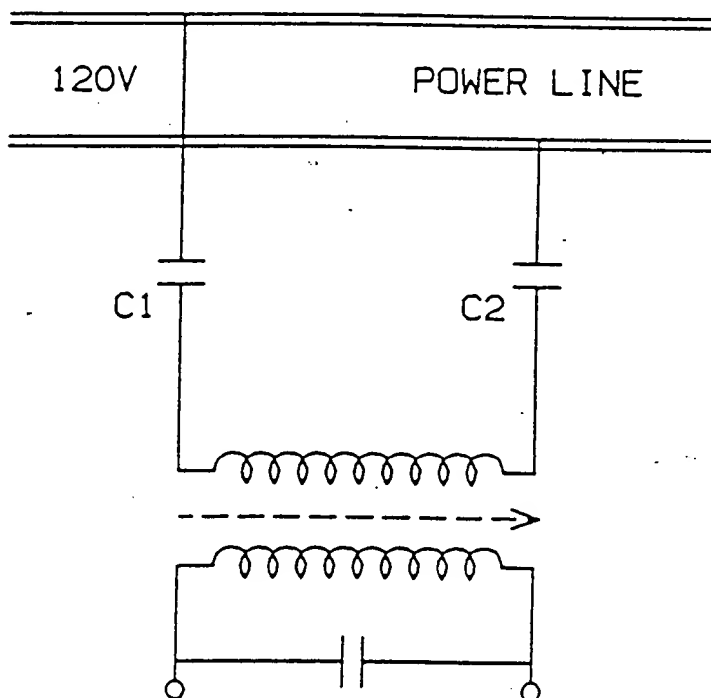
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Apparatus for power system communications includes a coupler at each of two or more locations along a pair of power-lines, the coupler having a pair of serial LC circuits with an air coil. A transmitter, a receiver, and a modem is also provided at each of the locations such that each of the serial LC circuits of the couplers resonate at a given frequency. The apparatus incorporates novel non-linear transformers which eliminate the signal from the power line and its harmonics, and which permit rapid transmission of signals for communications and other uses.

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POWER-LINE COMMUNICATION APPARATUSRelated Application

This application is a continuation-in-part of U.S. Serial No. 429,208 filed October 30, 1989 which is itself a continuation-in-part of U.S. Serial No. 344,907, filed April 28, 1989.

Background of the Invention

1. Field of the Invention

The present invention is related generally to power system communications, and more particularly to apparatus capable of simultaneously transmitting and receiving digital data signals both at high rates and over long distances through power-lines and through power line transformers, including AC, DC and coaxial cables (including phone lines).

2. Statement of the Prior Art

"Power-line carriers" are well known in the field of power system communications. The principal elements of such power-line carriers are transmitting and receiving terminals, which include one or more line traps, one or more coupling capacitors, as well as tuning and coupling equipment. Detailed information regarding the description and typical composition of conventional power-line carriers may be found in Fundamentals Handbook of Electrical and Computer Engineering, Volume II: Communication, Control, Devices, and Systems, John Wiley & Sons, 1983, pp. 617-627. TK151.F86, the contents of which are incorporated herein by reference.

A significant problem associated with such prior art power-line carriers is their requirement for one or more line traps, one or more coupling capacitors, one or more coupling transformers or one or more carrier frequency hybrid circuits and frequency connection cable. Furthermore, in traditional systems, the modulation at the transmitter and receivers is not synchronized. Traditional systems experience distance limitations whenever AM or FM demodulation is used, and they pick up the 60 Hz signal and its harmonics from the power-lines. To the extent that the carrier frequency is received at all, it is often too weak to demodulate. Such systems further have a narrow bandwidth and experience no less than a 20dB loss at the carrier

frequency.

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One prior art method operates at a frequency of between 20KHz and 400KHz where the attenuation of the power line is greater. However, the 60Hz harmonics are still picked up by such a system. Accordingly, there is still a need to use high power transmission because of noise and coupling losses of greater than 20dB. As a result, the signals must be transmitted over the power-lines at very high power outputs and low bandwidths.

Still other prior art methods operate below 20 KHz where the attenuation of the power-lines is lower. However, such systems experience a high level of noise and a very small bandwidth. These systems also experience at least a 20dB loss through the coupler.

All existing systems attempt to communicate between the harmonics rather than by reducing the noise significantly through the coupler. In addition, prior art systems are location dependent and are affected by their relative position with respect to transformers or other plugged in equipment. Frequently, prior art power line communication mechanisms must perform a frequency transponent in both the transmitter and receiver, thus requiring two or more quartz oscillators.

Finally, all previous power line communication systems are characterized by their incorporation of magnetic or ferrite (iron) core linear transformers for both transmission and reception in the duplexing system. Because these systems are magnetically coupled and the 60Hz current is greater than zero, they pass a significant amount of the 60Hz high power signal and its resulting harmonics.

The use of magnetic transformers for transmission is itself a cause of several problems. First, magnetic transformers are affected by distribution transformers and devices incorporating magnetically coupled transformers. Magnetic transformers tend to pass back large percentages of the 60Hz power-line currents which can damage the transmitter. The conventional response to this particular problem has been to increase the ratio of the primary to secondary windings to 10:1. While this results in a smaller "back" current passed to the transmitter, it consequently

requires high power transmission of the carrier signal. Further, systems using magnetic transformers do not resonate with the coupling capacitors used with such systems. Thus, such systems frequently experience a 20 (decibel) dB power loss over their associated coupling capacitor.

The problems associated with the use of magnetic transformers in receivers are equally significant. The use of magnetic linear transforms require the use of filters which pass a narrow bandwidth. As a result, prior art systems are slow (maximum of 100 baud). The transformer further picks up the magnetic field for every frequency and accordingly picks up the 60Hz signal and its harmonics. This further exacerbates the need for filtering in the receiver. In addition, the impedance of the primary of the magnetic transformer will be effected by the secondary side of the transformer which will not allow good matching conditions to the power line. This can result in mistuning which can be further aggravated by other power line transformers.

Prior art power line communications systems are also typically loud and require expensive repeaters which require at least 600 watts of power for transmission.

Prior art methods of telephone line communication also use magnetically coupled transformers which have similar narrow bandwidths and noise problems. The impedances of such systems do not match the impedance of the phone line well.

Figures 1-3 schematically illustrate the problems associated with prior art magnetic linear transformers as applied in power line communications systems. As can particularly be seen in Figure 3, such systems produce a narrow bandwidth and do not adequately attenuate the low frequency power signal and its harmonics.

The present invention, characterized by Figure 4, is directed to solving the above-mentioned problems. The present invention incorporates non-linear capacitively coupled air coil transformers coupled with respective resonating capacitor networks which minimize the 60Hz power signal and its harmonics, and which thereby simultaneously maximize the carrier signal for better transmission and reception of carrier frequencies. The

novel air coil transformers of the present invention permit communication directly through power line transformers over long distances and at low power transmission. In contrast to magnetic transformers characteristic of prior art systems, the non-linear transformers of the present invention experience gain for reception and transmission, and from a systematic standpoint, function as part of the power line.

The non-linear transformers of the present invention are capacitively coupled and will only pick up the frequencies for which they are designed. Because system noise is generated by the harmonics of the 60Hz power line signal and because the non-linear transformer passes none of the 60Hz signal, the majority of the harmonics are eliminated. The use of air coil transformers creates no impedance effect from the secondary side of the air coil and no impedance effect from other power line transformers. Consequently, impedance matching can be achieved using the resistivity of the primary air coil to the power line, which will be a function of part of the power line. The step-up or step-down aspects of power-line transformers are irrelevant using this coupling technique, because attenuation is equal in both directions. All of the above factors work to produce high speed power line communications over great distances.

The air coil transformers of the present invention permit high speed, high band power line communication at frequencies up to 1 MHz (with less than about a 200 KHz bandwidth) for applications including LAN (local area networks) and phone line communications; communication at frequencies up to 160 KHz with about a 20 KHz bandwidth for high distance, high voltage and LAN communications; and communication at frequencies up to 35 KHz (preferably 7-15KHz) with about a 6 KHz bandwidth for communication through any power line transformer. Finally, the novel air coil transformers of the present invention are equally applicable to any high voltage DC communications preferably up to 160 KHz.

In view of the above, it is an object of the present invention to provide a power line communications apparatus which utilizes novel non-linear transformers for both transmission and

reception.

It is a further object of the present invention to provide power line communication apparatus utilizing novel air coil transformers which can be used for phone line, coaxial, LAN, power line and power line communication through power line transformers.

It is an additional object of the present invention to provide a power line communication apparatus in which the primary coil of the transformer resonates with an associated coupling capacitor network in order to maximize the transmission and reception voltages at the respective carrier frequencies. This resonance effectively creates a band pass filter at carrier frequency.

It is still a further object of the present invention to provide a communications apparatus in which a non-linear transmission transformer has primary and secondary windings in which the ratio of the windings is about 1:1.

It is still yet a further object of the present invention to provide a communications apparatus in which the receiver coupling contains a capacitor network which impedes the 60Hz high power signal and its harmonics.

It is still yet a further object of the present invention to provide a communications apparatus in which the receiving network includes a non-linear air coil transformer in which the ratio of the primary to secondary windings is about 1:1.

It is still yet a further object of the present invention to provide a communications apparatus in which the capacitor network for both transmission and reception include resistors which divide down the AC voltage evenly. The resistors also serve to protect the system against spiking and lightning.

It is still yet a further object of the present invention to provide a communications apparatus which can provide a high bandwidth for the transmission of communications signals at speeds greater than 9600 baud, and at speeds of up to 1200 baud directly through power line transformers.

It is yet a further object of the present invention to provide a communications apparatus containing a non-linear air coil transformer effectively comprising two single layer finite

solenoids each having different diameters thus defining an air gap, which creates a small coupling capacitance between the solenoids.

It is still yet a further object of the present invention to provide apparatus for power system communications over long distances.

It is still yet an additional object of the present apparatus to provide power line communications in which the primary and secondary coils of the non-linear transformer have different diameters.

It is yet another object of the present invention to provide an apparatus for power line communications in which coupling capacitor resonates with the primary side of the non-linear transformer.

It is still a further object of the present invention to provide a novel non-linear air coil transformer coupled with a capacitor network for use in telephone line communications.

Summary of the Invention

In accordance with the present invention, apparatus for power-line communications is disclosed. The power line communication apparatus comprises; modulator means for modulating a carrier signal having a first frequency to be transmitted over a power line; transmitter means for transmitting said modulated carrier signal having said first frequency to a coupler means; and coupler means comprising capacitor means connected to a power line and non-linear transformer means coupled to said transmitter means for transmitting said transmitted modulated carrier signal having said first frequency to said capacitor means over said power line.

In accordance with a major aspect of the present invention, air coils comprising primary and secondary air windings function (with resonating capacitor networks) as the non-linear transformer (high pass filter) which cut the 60Hz harmonics below 10KHz with at least 80dB attenuation. Because the air windings (which function as solenoids) create a small coupling capacitance through the air gap, the secondary windings, with the coupling capacitance, function as a high pass filter.

The communications apparatus of the present invention has numerous applications. The main applications are in electricity and gas meter readings, the switching of remote control devices, and data communications between computers over power-lines. By way of example, the present invention makes it possible to transmit electricity and gas meter readings over power-lines for large numbers of customers. Such readings can be transmitted at low power, at high data rates, over long distances and directly through power line transformers. In a hypothetical system, such readings could be made by a computer with addressable data using two frequencies from house (120/240/480 Volts), to the distribution line, and directly through the distribution transformer (13,800, 22,000, 69,000 voltage power-lines). In addition, public phone systems in trains and internal security systems in homes could be set up over high voltage power-lines using addressable data transmitted through the phone system.

The present invention can be further utilized to control large or small machines in factories and mines. The apparatus

of the present invention has been used to transmit data between computers and printers at speeds in excess of 9600 baud. Other applications include data transmission through phone lines, coaxial lines and any high voltage DC power lines.

Other objects, advantages, and novel features of the present invention will become more apparent from the following detailed description thereof, when considered in conjunction with the accompanying drawings wherein:

Brief Description of the Drawings

Figs. 1 and 2 schematically represent traditional duplexing couplers on both low and high voltage power lines.

Fig. 3 illustrates the frequency characteristics of traditional serial LC couplers.

Fig. 4 schematically represents the LC coupler of the present invention.

Fig. 5 illustrates the frequency characteristics of the LC coupler of the present invention.

Fig. 6 is a block diagram of a power-line communication apparatus in accordance with the present invention;

Fig. 6A is a block diagram of a power-line communication apparatus in accordance with the present invention including power-line transformers;

Fig. 7 is a schematic diagram of first coupling means in accordance with the present invention, which corresponds to the coupling TA-RB shown in Figs. 6 and 6A;

Fig. 8 is a schematic diagram of second coupling means in accordance with the present invention, which corresponds to the coupling TB-RA shown in Figs. 6 and 6A;

Figs. 9A and 9B illustrate the non-linear transformer air coils utilized in the present invention.

Fig. 9C illustrates a half duplexing coupler in accordance with the present invention for data communications through distribution transformers.

Fig. 10A is a schematic diagram corresponding to the modulator FA/demodulator FB shown in Figure 6.

Fig. 10B is a schematic diagram of an alternative modulator FA/demodulator FB for the system in Fig. 6.

Fig. 10C is an FSK decoder phase lock loop which can function as the modulator/demodulator circuit of Fig. 6;

Fig. 10D is the primary phase lock loop of Fig. 10A;

Fig. 11 is a schematic diagram of a transmitter means used in the present invention;

Fig. 12 is a schematic diagram of receiver means used in conjunction with the transmitter means shown in Fig. 11, in the power-line communication of data signals over long distances.

Fig. 12A is a schematic diagram of a receiver which can be

used for high speed communications.

Fig. 13 is a schematic representation of a coupling for the power line from phase to ground.

Fig. 14 is a schematic representation of a three phase coupling to the powerline, three phases to ground.

Fig. 15 illustrates a two phase coupling connection to the power line, phase to phase.

Fig. 16 shown a three phase transformer coupling of the type predominantly used in Europe.

Fig. 17 shows a one phase transformer coupling of the type generally used in the United States.

Fig. 18 shows a spread spectrum transmitter/receiver in accordance with the present invention which is particularly applicable for communication in between noise.

Fig. 19 Bi-Polar Shift Keying transmitter/receiver which can be utilized with the present invention.

Fig. 20 is an equivalent circuit of the upper and underground power line with the power line impedances.

Fig. 21 is a graph of power line attenuation versus carrier frequency on the 35 KVAC power line for a 20 KM distance.

Fig. 22 is an illustration of an electric meter reading system incorporating the communication system of the present invention which may be implement by a utility.

Fig. 22A is a block diagram illustrating the use of the couplers of the present invention within a LAN linked by power lines or conventional phone lines.

Fig. 23 is a block diagram of the system of Figure 22 as applied to a multiplicity of substations.

Fig. 24 is a simplified block diagram of the system of Fig. 22.

Fig. 25 is a block diagram of a power line communication system.

Detailed Description of the Invention

Referring now to the Figures, wherein like numbers designate like or corresponding parts throughout each of the several views, there is shown in Figs. 6 and 6A block diagrams of a power-line communication apparatus 10 according to the present invention for use in low power applications (up to 480 VAC).

The communications apparatus 10 shown is coupled to a pair of power-lines 12, and generally comprises first coupling means 14, first transmitter means 16, first receiver means 18, and first modulator/demodulator means 20 at a first location along the power-lines 12. The combination of transmitter means 16, receiver means 18 and modulator/demodulator means 20 comprise a first modem means 21. At a second location along power-line 12 are second coupling means 22, second transmitter means 24, second receiver means 26, and second modulator-demodulator means 28. The combination of transmitter means 24, receiver means 26 and modulator/demodulator means 28 comprise a second modem means 23.

As will be explained in greater detail herein below, both coupling means 14, 22 include a pair of serial LC circuits (Figs. 7 and 8) which are coupled to the pair of power-lines 12. Referring to Fig. 6A, the apparatus is coupled to power-line transformers 27. Each of the serial LC circuits in a respective one of the coupling means 14, 22 resonate at a given frequency. The LC circuits include a plurality of capacitors which are connected in a series and parallel configuration. See Figure 4. The coupling means 14, 22 further incorporates novel non-linear aircoil transformers for both transmission and reception which serve as the inductive (L) component of the respective LC circuits. It is to be noted that while the present invention is being described in the context of two identical communications apparatus, either circuit may be configured to function as a simple receiver or transmitter.

The first transmitter means 16, coupled to the first coupling means 14, is capable of transmitting digital data signals carried by a first carrier frequency FA across the pair of power-lines 12, and as shown in Fig. 6A, through power line transformers. The first receiver means 18, coupled to the first coupling means 14, is capable of receiving digital data signals

carried by a second carrier frequency FB from the pair of power-lines 12. The modulator/demodulator means 20, coupled between the first transmitter means 16 and the first receiver means 18, modulates the digital data signals to be carried by the first carrier frequency FA, and demodulates the digital data signals carried by the second carrier frequency FB.

In a similar manner, at the second location along the power-lines 12, the second transmitter means 24 is coupled to the second coupling means 22. Second transmitter means 24 is capable of transmitting the digital data signals to be carried by the second carrier frequency FB across the pair of power-lines 12, and as shown in Fig. 6A, through power-line transformers. Accordingly, the second receiver means 26 is coupled to said second coupling means 22, and is capable of receiving the digital data signals carried by the first carrier frequency FA from the pair of power-lines 12. The second modulator/demodulator 28, coupled between the second transmitter means 24 and the second receiver means 26, modulates the digital data signals to be carried by the second carrier frequency FB and demodulates the digital data signals carried by the first carrier frequency FA.

The first and second carrier frequencies FA, FB preferably comprise frequencies up to 1MHz (megahertz), at a power level of about 20 decibels above any other frequencies. The bandwidth of each of the coupling means 14, 22 preferably comprises less than 30 kilohertz. For most high voltage, long distance communications, the first and second carrier frequencies FA, FB will typically comprise frequencies that are less than about 160 KHz, having bandwidths of less than 20 KHz. When used for communication through power line transformers, FA and FB will typically comprise frequencies below 35 KHz (preferably 7-15 KHz) with bandwidths of about 6 KHz. The serial LC circuits (Figs. 7 and 8) of both coupling means 14, 22 each comprise impedance matching means which will be described in greater detail below.

With reference next to Figs. 7 and 8, the specific circuitry for representative coupling means 14, 22 is now described in greater detail. The coupling means 14 (Fig. 7), 22 (Fig. 8) each include a pair of serial LC circuits 30, 32 which resonate at the carrier frequencies FA, FB. It will be appreciated by those

skilled in the art that for FSK (Frequency Shift Key) applications FA will correspond to F_1 and F_2 and FB will correspond to F_3 and F_4 . The serial LC circuit 30 shown in Fig. 7 resonates at the second carrier frequency FB, while serial LC circuit 32 resonates at the first carrier frequency FA. Similarly, the serial LC circuit 30 of Fig. 8 resonates at the first carrier frequency FA, and serial LC circuit 32 resonates at the first carrier frequency FB.

The LC circuits include respective serially and parallelly connected capacitor networks 34, 42. To each capacitor in series is connected a resistor 35 and 45 which evenly divides down the AC voltage. Preferably, the resistor values should be rated at 1 Megaohm per 5 watts and the capacitors should be 200 VAC capacitors. The resistors should preferably be thick film (i.e. carbonless). The Q point of the capacitors should similarly be high. In operation, the couplers (LC) should be placed into a resin for good insulation when used with operating voltages up to to 22 KV. At operating voltages above 22 KV, the capacitors should be separately placed in an oil filled insulator and the air coil transformer placed into a resin. The use of the resistors 35, 45 serve to minimize the DC current so as to prevent spiking and afford lightning protection.

It is to be appreciated that the capacitor networks 34, 42 create equivalent capacitances $C_{(eq1)}$ and $C_{(eq2)}$ for transmission and reception, respectively. The capacitor networks are connected to non-linear air coil transformers to be discussed below which function as the inductive element (L) of the LC circuit. $C_{(eq1)}$ and $C_{(eq2)}$ resonate with the primary windings of the non-linear transformers.

The air coil means comprise a first air coil 36 which includes a primary winding 38 and a smaller secondary, winding 40 situated coaxially within the primary winding. The second serial LC circuit 32 includes second air coil 44 including a primary winding 46 and smaller secondary winding 48 situated coaxially within the primary winding.

The first plurality of capacitors 34 are connected together in parallel between one of the power-lines 12 and the primary winding 38 of the first air coil 36. The primary winding 38 of

the first air coil 36 is thereafter serially connected to the other power-line 12. The secondary winding 40 of the first air coil 36 is connected to its respective transmitter means 16. The second plurality of capacitors 42 are serially connected together between one of power-lines 12 and the primary winding 46 of the second air coil 44. The primary winding 46 of the second air coil 44 thereafter being serially connected to the other power-line 12. As noted above resistors, 35 and 45 function to evenly divide the voltage and serve to minimize spiking and afford lightning protection.

Referring to Figs. 9A-9C, the non-linear air coil transformers of the present invention are described in greater detail. The novel air coil structures function as respective non-linear capacitively coupled air coil transformers for both transmission and reception. Figure 9A illustrates the transmitter transformer 36 with coupling capacitor network C_{eq1} . As shown in Fig. 9A, the transmitter transformer 36 is connected in series with C_{eq1} and the power line 12. The transformer is non-linear and comprises a primary winding 38 and coaxial smaller secondary winding 40 which is placed between the primary winding. The primary winding 38 has a winding diameter $2R$ 39 which is greater than the diameter of the secondary winding $2r$ 41 and accordingly creates an air gap between the two. Of particular significance is the fact that both the primary and secondary windings 38, 40 in the transmitter air coils have the same numbers of turns (designated by $N_1 = N_2$), and are thus at a 1:1 ratio. Accordingly, the transmitter doesn't require a high transmission voltage, as is characterized by prior art devices. The primary coil resonates with C_{eq1} , thereby achieving a gain on the secondary side. Further C_{eq1} is set to resonate with the primary winding at the carrier frequency F_A , thus creating a band pass filter at the carrier frequency F_A . This maximizes the current at the carrier frequency F_A .

The values of C_{eq1} and the resistors 35, 45 are set to generate a large voltage loss at frequencies less than 10KHz (thus encompassing the 60Hz power line signal). Thus, the significantly reduced 60Hz signal cannot generate a large enough current to pass the created small capacitance. That is, for

transmission, the resistivity of the primary coil is roughly equal to the input impedance of the power line.

The receiver transformer is now described with respect to Fig. 9B. The receiver is connected to the power line 12 via C_{eq2} . As with the transmitter of Figure 9A, the receiver air coil comprises a non-linear transformer having a primary winding 46 with a first diameter $2R$ 47 and a secondary coaxial winding 48 having a second diameter $2r$ 49. Accordingly, an air gap, and thus a coupling capacitance, is similarly created between the respective primary and secondary windings 46, 48. In the receiver transformer, the ratio of the primary and secondary windings must be greater than or equal to 1:1, at carrier frequencies below 1MHz and may be below 1:1 at carrier frequencies greater than 1MHz. While this ratio can be altered or modified, such a change requires a resultant alteration in the size of the air gap, i.e. the relative ratio of $2R$ and $2r$. The capacitor network $C_{(eq2)}$ is set to resonate with the primary winding at carrier frequency FB , thus creating a band pass filter at carrier frequency FB .

In operation, the power line voltage is significantly reduced by C_{eq2} and the resistors. Thus, the created capacitance with the secondary winding significantly attenuates the harmonics and 60Hz signal to about zero, thus effectively functioning as a high pass filter. The carrier frequency voltage is thereby maximized. The air coil produces a signal having a wider bandwidth than previous systems. The bandwidth characteristics of the present invention are shown in Figure 5. For reception, the resistivity of the primary should be greater than the impedance of the power line.

From a design standpoint, then, the philosophy is to minimize the 60Hz line voltage and its harmonics. The circuit can be thought of as a series CRL circuit on the transmission side where: for the primary;

$$V_{PRIMARY(60Hz)} = V_{power-line} (Z_l)/(Z_c)$$

and for the secondary;

$f^2(\text{carrier})/f^2(60Hz)$, determines the $V_{carrier}/V_{60Hz}$ frequency characteristic ratio which will always be around 100dB or greater. Preferably, a higher carrier frequency should be used

for higher power line voltages. On the receiver side, the ratio of the impedances of inductance to capacitance, i.e. Z_L/Z_C must be minimized. Thus, Z_C should be maximized at 60Hz. Consequently, because $I_{60Hz} = V_{PL}/Z_C$, Z_C should be maximized at 60Hz.

The above relationships coupled with the non-linearity of the transformers (i.e. the existence of the air gap) serve to completely filter the 60Hz current and its harmonics below 10KHz. The above makes it possible to communicate directly through power line transformers. It is to be appreciated by those skilled in the art that the noise component of the 60Hz signal is concentrated below 10KHz. Because system noise is generated by the harmonics of the 60Hz power line signal and because the non-linear transformer passes none of the 60Hz signal, the majority of the harmonics are eliminated. The use of air coil transformers creates no impedance effect from the secondary side of the air coil and no impedance effect from other power line transformers. Consequently, impedance matching can be achieved using the resistivity of the primary air coil to the power line, which will be a function of part of the power line. The step-up or step-down aspects of power-line transformers are irrelevant using this coupling technique, because attenuation is equal in both directions.

The theoretical operation of the circuit is seen with reference to Fig. 20, an equivalent circuit of the upper and underground power line, which also shows the LRC values required to match the coupler to the power line. At primary resonance, the LC impedances will be zero at transmission and reception such that the resistivity of the primary coil R_T matches the input impedance of the power-line. On the receiver side, R_R , has to be larger than the input impedance of the power line. These relationships facilitate long distance communication.

The coupling means 14, 22 shown in Figs. 6, 7, 8, 9A and 9B are suitable for communication in association with wide range of power-line voltages. As will be discussed herein, they can be utilized for high voltage, low voltage, LAN and phone line communications, as well as for communication directly through power line transformers.

A. Communication Options1. Computer communication through Power and Phone Lines

The couplers of the present invention can be applied to LAN (local area network) and phone line communications and facilitate communication speeds up to 10 Kilobaud. For this application, the coupling means 14 preferably use a first carrier frequency FA of around 75 KHz (and 81.5 KHz for FSK) and a second carrier frequency FB of around 111 KHz (and 117.5 KHz for FSK) over power-lines 12 of up to about 1KVAC. The coupler preferably uses first and second pluralities of capacitors 34, 42 as shown therein, each capacitor having a 1.6KV working voltage and a capacitance of 100 nanofarads. The first air coil 36 should have a primary winding 38 with a coil diameter of 2.2cm, #26 gauge magnet wire secondary winding 40 with a coil diameter of about 1.6 cm, #34 gauge magnet wire. The second air coil 44 should have a primary winding 46 of 2.2 cm, #34 gauge magnet wire and a secondary winding 48 with a coil diameter of about 1.6 cm, #30 magnet gauge wire. The system utilizes the modems shown in Figures 10A, 11 and 12A.

On the other side of the system, coupling means 22 comprises first and second pluralities of capacitors 34, 42 as shown therein, each capacitor having a 1.6KV working voltage and a capacitance of 100 nanofarads, along with the non-linear air coil transformer. As above, the first air coil 36 should have a primary winding 38 with a coil diameter of 2.2 cm, #26 gauge magnet wire and a secondary winding 40 with a coil diameter of 1.6 cm, #34 gauge magnet wire. The second air coil 44 should similarly have a primary winding 46 of about 2.2 cm, #34 gauge magnet wire and a secondary winding 48 with a coil diameter of about 1.6 cm of #30 gauge magnet wire.

2. High Voltage Power Line Communications

The couplers are also applicable to high voltage power line communication applications in which a 15 KVDC/4.5KVAC capacitor can be used for power-line voltages of up to 750KV. The couplers of the present invention can be utilized for communication speeds up to 9600 baud. In this application first FA and second FB carrier frequencies of 80 KHz and 120 KHz, respectively, are

Additionally, as shown in Figure 22A the high speed phone line and LAN couplers of the present invention could be used within the utility to connect local workstations 141 to the central computer 139. For example, a clerical worker situated at a work station may access the VAX computer through the power lines of the facility via modems and high speed LAN or phone line couplers of the present invention at data transmission speeds of up to 10 Kbaud.

Figure 23 is a block diagram of an expanded system which may be utilized by a utility to meter a multiplicity of substations. In this embodiment the central computer would simultaneously read a large number of meters via a master modem and multiplexer coupled to a multiplicity of couplers 143. As shown, the computer communicates with each substation (1, 2, 3, etc.) over conventional phone lines. The respective substations then communicate with the individual meters at 1200 baud via high voltage distribution lines and through distribution transformers. Figure 24 is a simplified block diagram of the communication system of Figure 22. Figure 25 is a block diagram of how the couplers of the present invention can be utilized to communicate through two power line transformers 145 and through a three phase large transformer 147. In this configuration, the couplers will comprise low voltage couplers designed for communication through power line transformers as discussed above. It is to be noted that the couplers of the present invention will permit the simultaneous transmission and reception of more than one carrier frequency through the couplers. Hence, the couplers can be simultaneously utilized by an electric utility for electric meter reading at a first frequency while a water utility utilizes the couplers at a second carrier frequency for water meter reading.

A final consideration of the present invention is the connection of the apparatus to a three phase power line. Figure 13 illustrates the general case of coupling the apparatus to the power line, phase to ground. In this format, the carrier frequency is undetectable by other phase-ground coupling connections and each phase is isolated from each other for communication purposes. Figure 14 illustrates a special three phase coupling connection to the power line, 3 phases to ground.

This system utilizes all three phases from the power line and ground for communication. In this case, the carrier frequency is detectable on any other phase-ground coupling connection. In this manner, the phases are interconnected for communicating purposes.

Figure 15 illustrates a special two phase coupling connection to the powerline, phase to phase 147. This system utilizes two phases from the power line for communication. The carrier frequency is detectable only on the two phase coupling connection. In this configuration, only the coupled two phases are connected for communication purposes.

Figure 16 illustrates a three phase transformer coupling around delta and Y (Wye) transformers 149. This coupling system is generally utilized in Europe. The carrier frequency is detectable on the other power line. In this manner, two different high voltage power lines are connected to each other for communication purposes. Finally, Figure 17 illustrates a one phase transformer coupling which is generally used in the U.S.A. In this manner, the carrier frequency is detectable on the other power line. Accordingly, two different high voltage power lines are connected to each other for communication purposes.

It is to be understood, therefore, that within the scope of the appended claims, the present invention may be practiced otherwise than as specifically described herein.

first coupling means, including a pair of serial LC circuits, coupled to the pair of power-lines;

first transmitter means, coupled to said first coupling means, for transmitting signals carried by a first carrier frequency across the pair of power-lines;

first receiver means, coupled to said first coupling means, for receiving signals carried by a second carrier frequency from the pair of power-lines;

first modem means, coupled between said first transmitter means and said first receiver means, for modulating said signals to be carried by said first carrier frequency and for demodulating said signals carried by said second carrier frequency;

second coupling means, including a pair of serial LC elements, coupled to the pair of power-lines;

second transmitter means, coupled to said second coupling means, for transmitting said signals to be carried by said second carrier frequency across the pair of power-lines;

second receiver means, coupled to said second coupling means, for receiving said signals carried by said first carrier frequency from the pair of power-lines; and

second modem means, coupled between said second transmitter means and said second receiver means, for modulating said signals to be carried by said second carrier frequency and for demodulating said signals carried by said first carrier frequency.

16. The duplexing apparatus according to claim 15, wherein one of said serial LC circuits of both of said first and second coupling means comprises a first plurality of capacitors and a first air coil including primary and secondary windings, the diameter of said primary winding being greater than the diameter of said secondary winding thereby creating an air coil between said primary and secondary windings, while the other serial LC circuit comprises a second plurality of capacitors and a second air coil including primary and secondary windings, the diameter of said primary winding being greater than the diameter of said secondary winding thereby creating an air core between said primary and secondary windings, wherein said first plurality of

capacitors are connected together in parallel between one of the power-lines and said primary winding of said first air coil, said primary winding of said first air coil thereafter being serially connected to the other power-line, and said secondary winding of said first air coil is connected to its respective transmitter means, and wherein said second plurality of capacitors are serially connected together between said one of the power-lines and said primary winding of said second air coil, said primary winding of said second air coil thereafter serially connected to the other power-line.

- 17. The communications apparatus according to claim 15, wherein said first and second coupling means each have a bandwidth of less than about 200 kilohertz.

18. The communications apparatus according to claim 15, wherein said first and second coupling means each have a bandwidth of less than about 20 kilohertz.

19. The communications apparatus according to claim 15 wherein the primary and secondary windings of said first and second air coils function as a non-linear transformer.

20. The communications apparatus according to claim 15 wherein the primary and secondary windings of said first and second air coils function as a capacitively coupled transformer.

21. The communications apparatus according to claim 15 wherein the ratio of the number of turns of said primary to secondary coil in said first air coil means is about one to one.

22. The communications apparatus according to claim 15 wherein the ratio of the number of turns of said primary to secondary coil in said second air coil means is about one to one.

23. The communications apparatus according to claim 15 wherein the created capacitance created between the primary and secondary windings of said air coils function as a high-pass filter with the secondary windings.

24. The communications apparatus according to claim 15 wherein the primary windings with the plurality of capacitors function as a band-pass filter.

25. The communications apparatus according to claim 15 wherein said first plurality of capacitors includes resistor means to evenly divide down the voltage over said first plurality

of capacitors.

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26. The communication apparatus according to claim 25 wherein said second plurality of capacitors includes resistor means to evenly divide down the voltage over said second plurality of capacitors.

27. The communication apparatus according to claim 25 wherein said first plurality of capacitors resonates with the primary winding of said first air coil.

28. The communication apparatus according to claim 25 wherein said second plurality of capacitors resonates with the primary winding of said first air coil.

29. In a power line communication apparatus, an improved coupler comprising capacitor means coupled to a power line and non-linear transformer means comprising a primary coil having a first diameter, said primary coil being coupled to said capacitor means, and a secondary coil extending coaxially within said primary coil such that an air gap is created between said primary and secondary coils.

FIG. 1

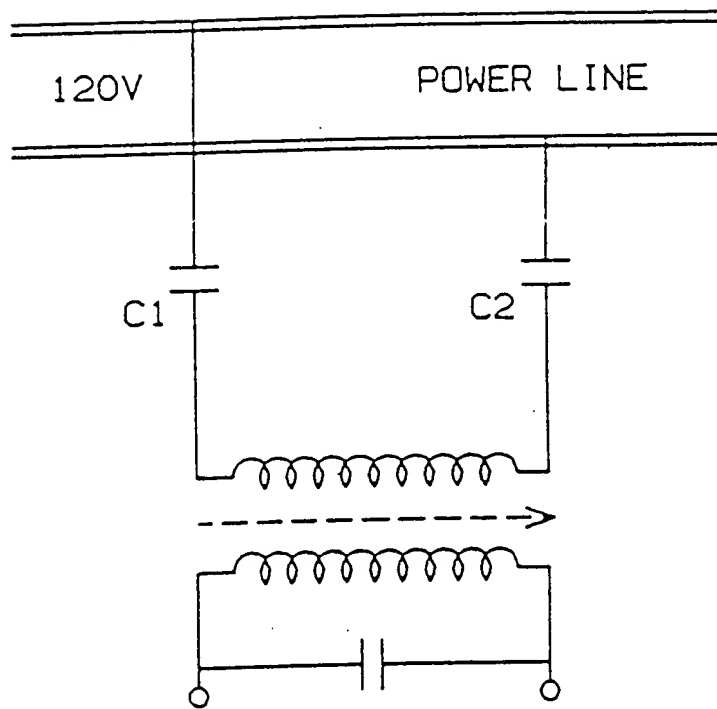
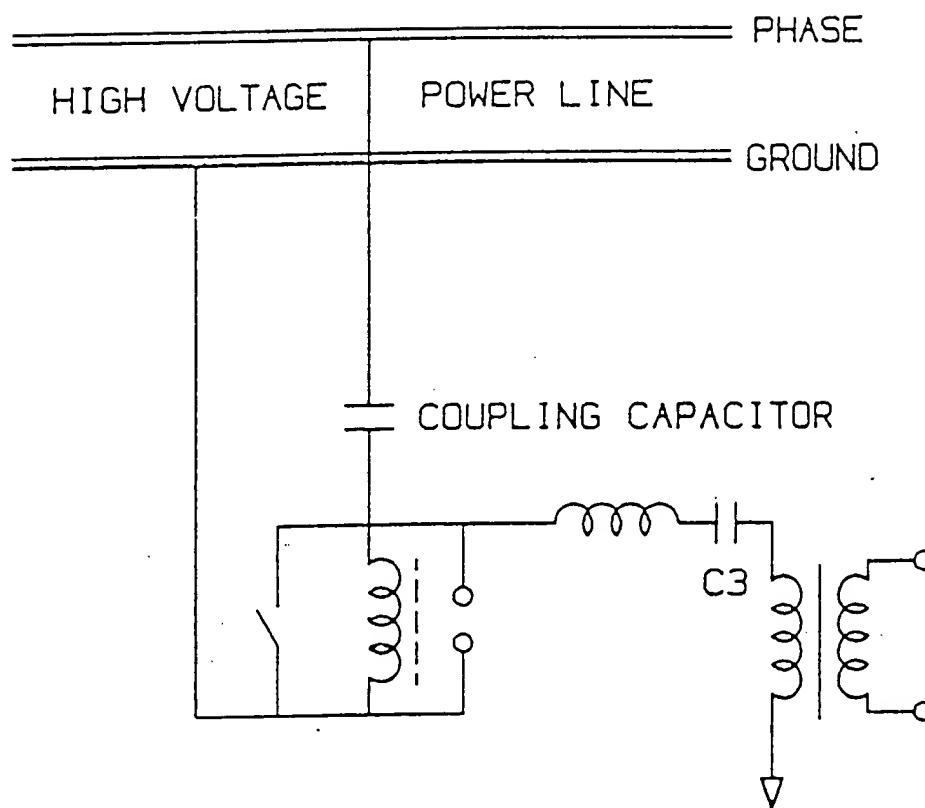
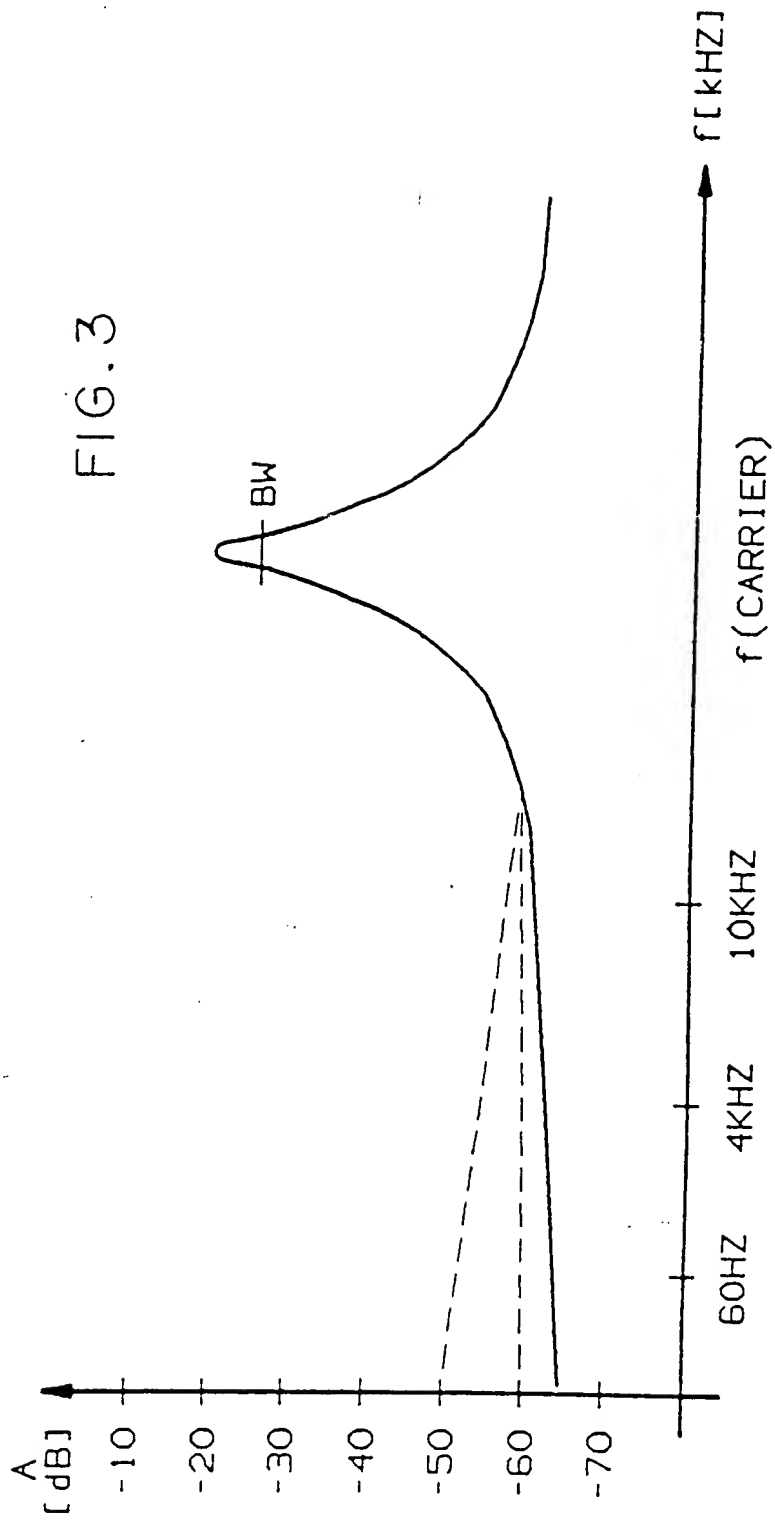


FIG. 2

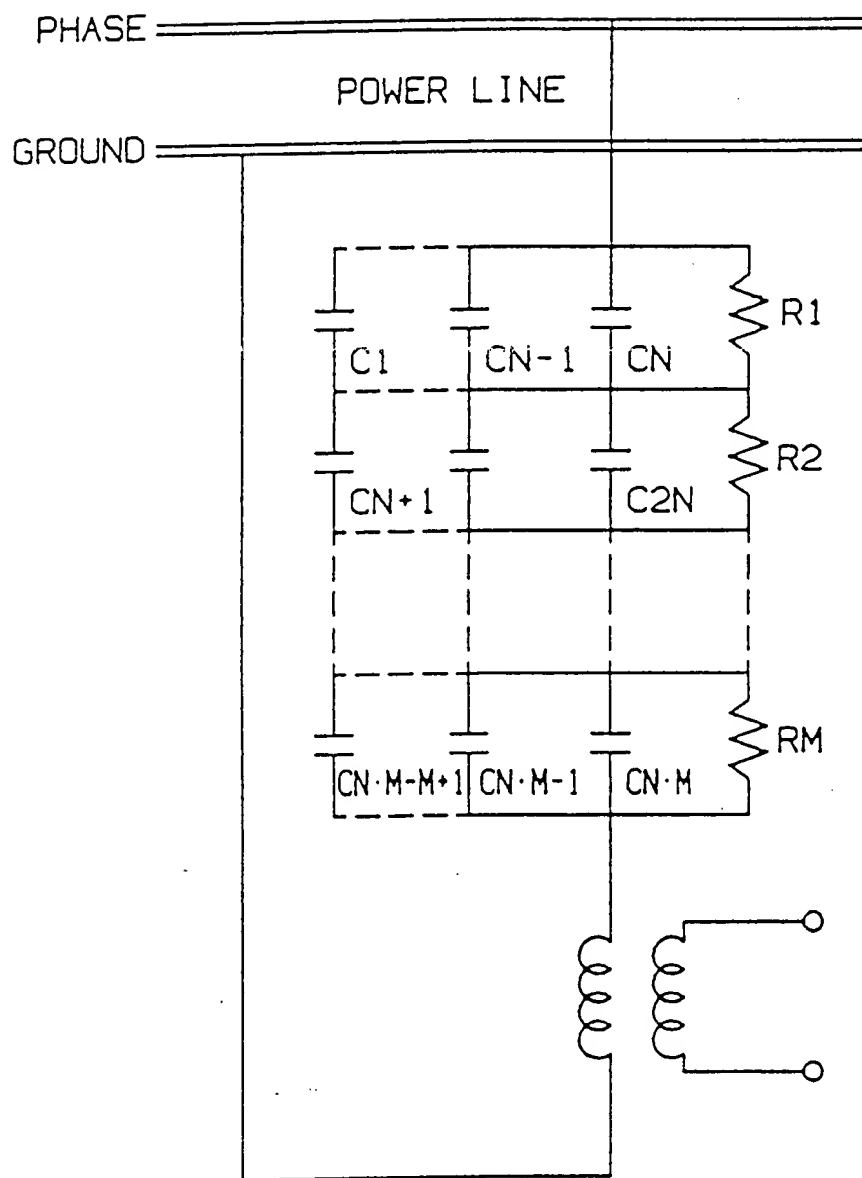


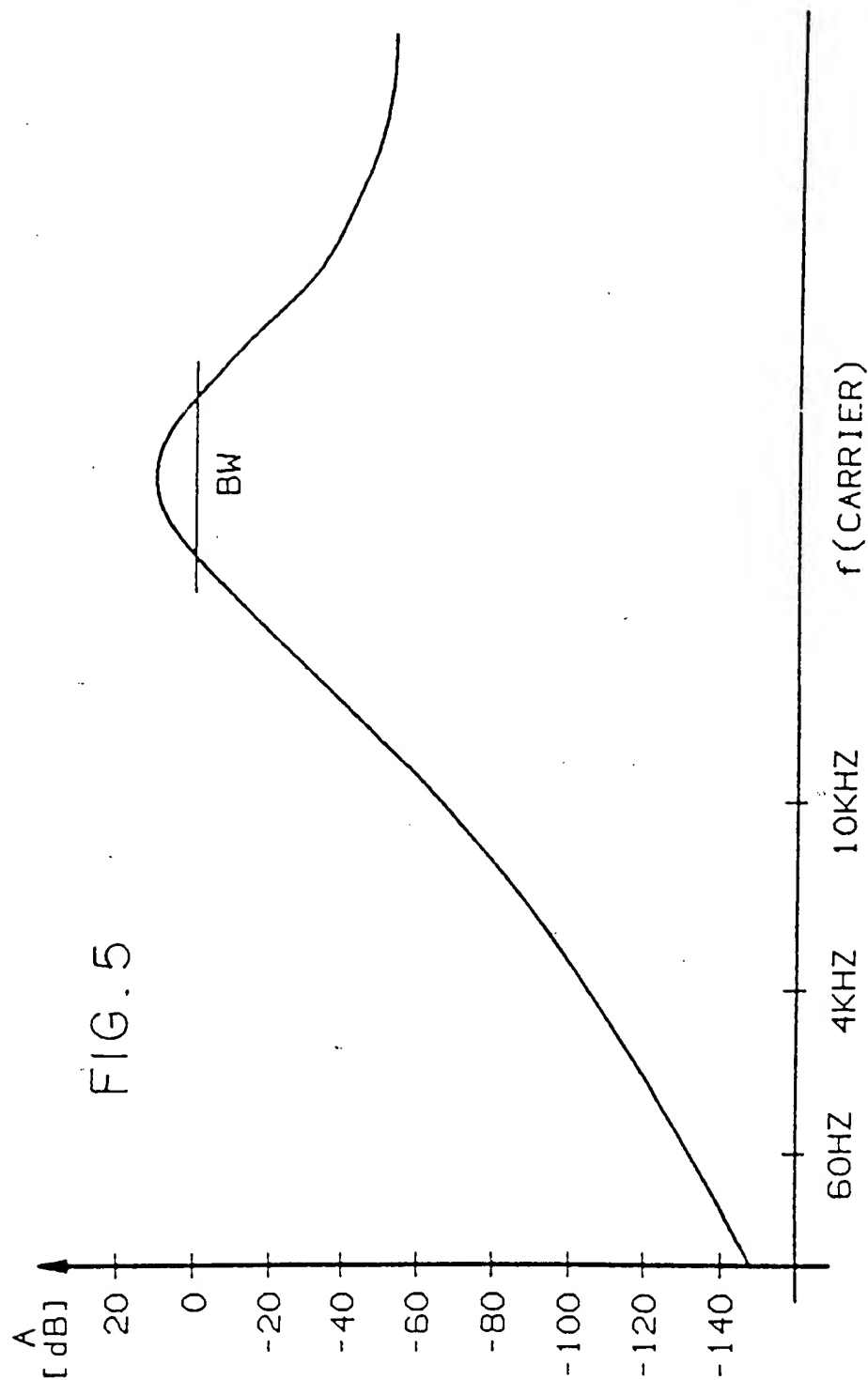
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FIG. 4





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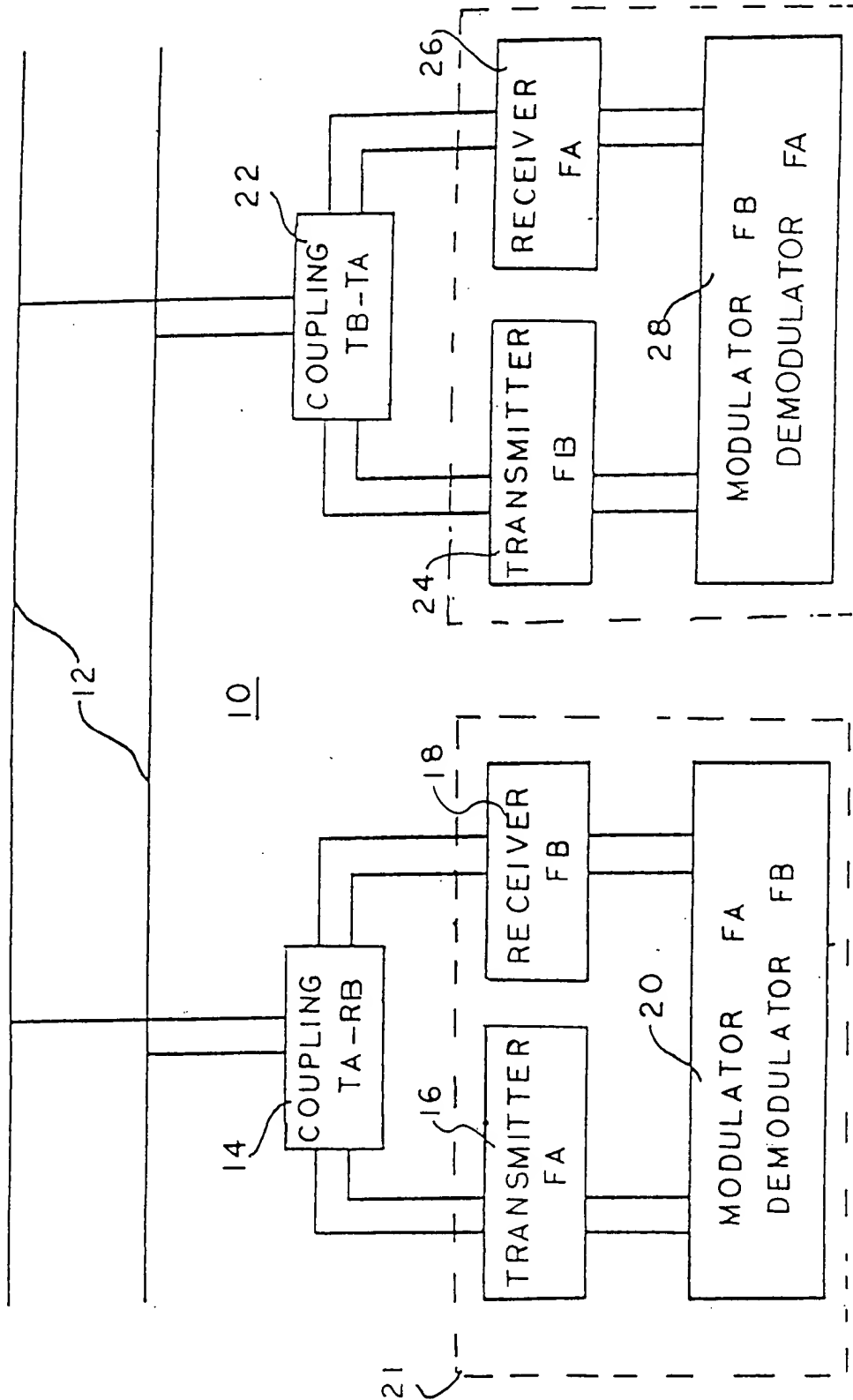


FIG. 6

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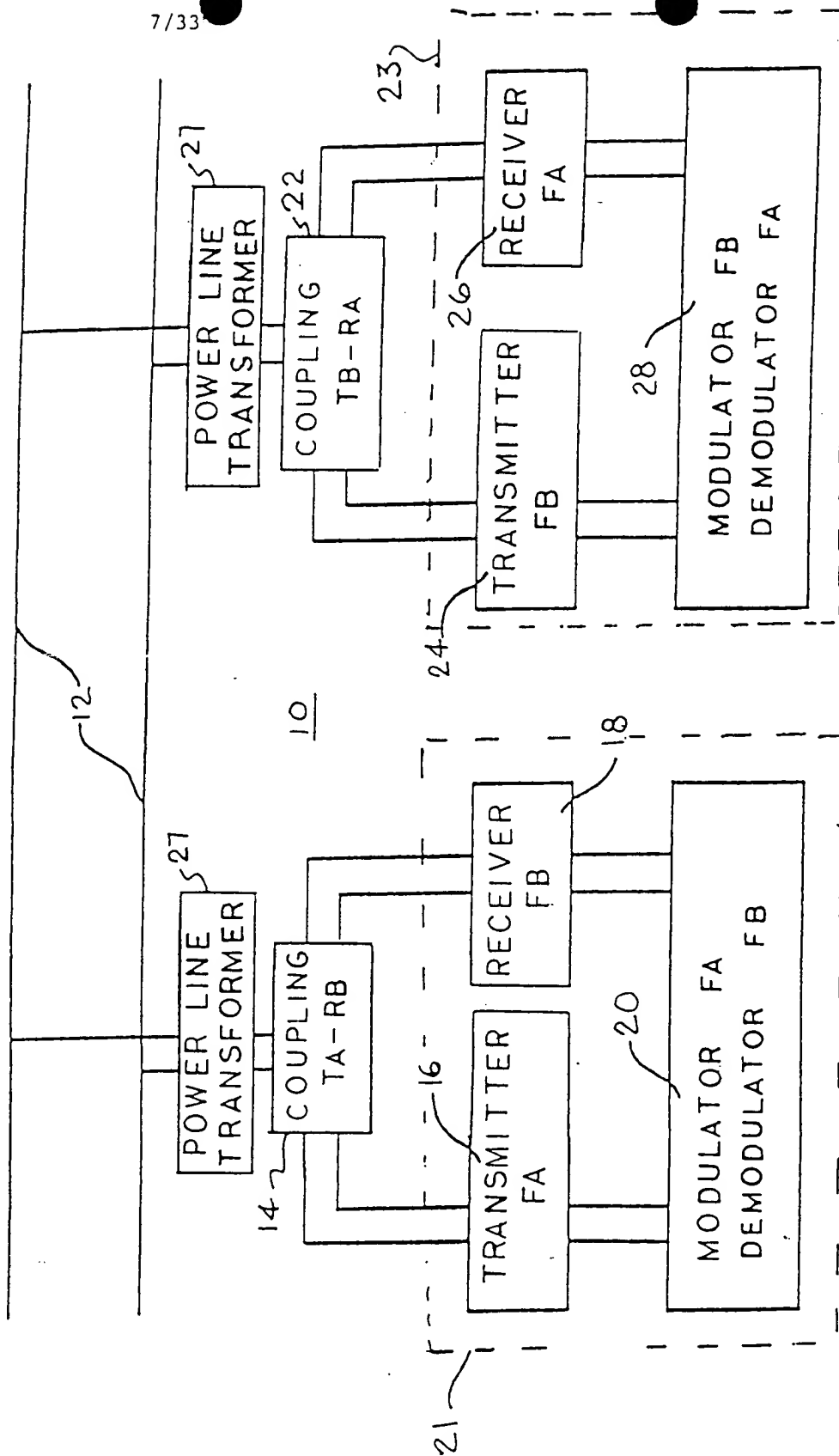


FIG. 6A

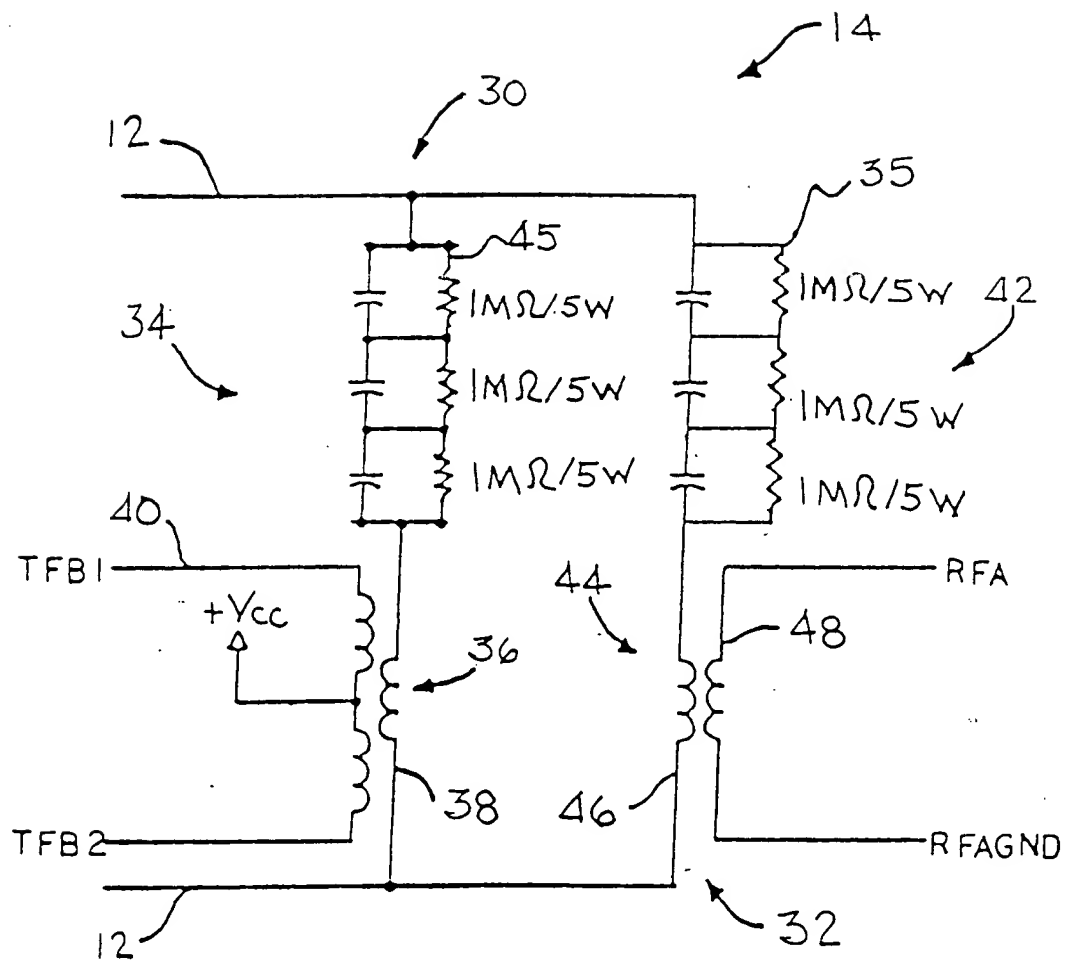


FIG. 7

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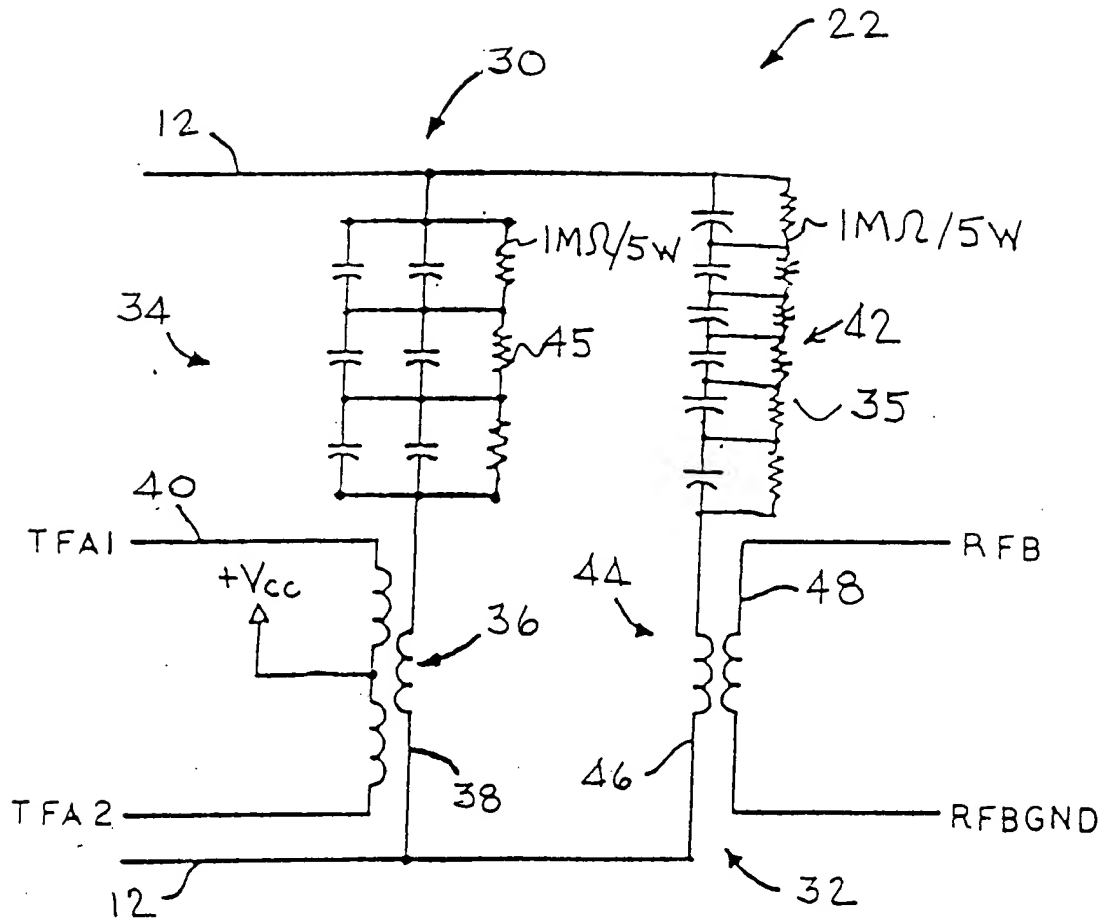
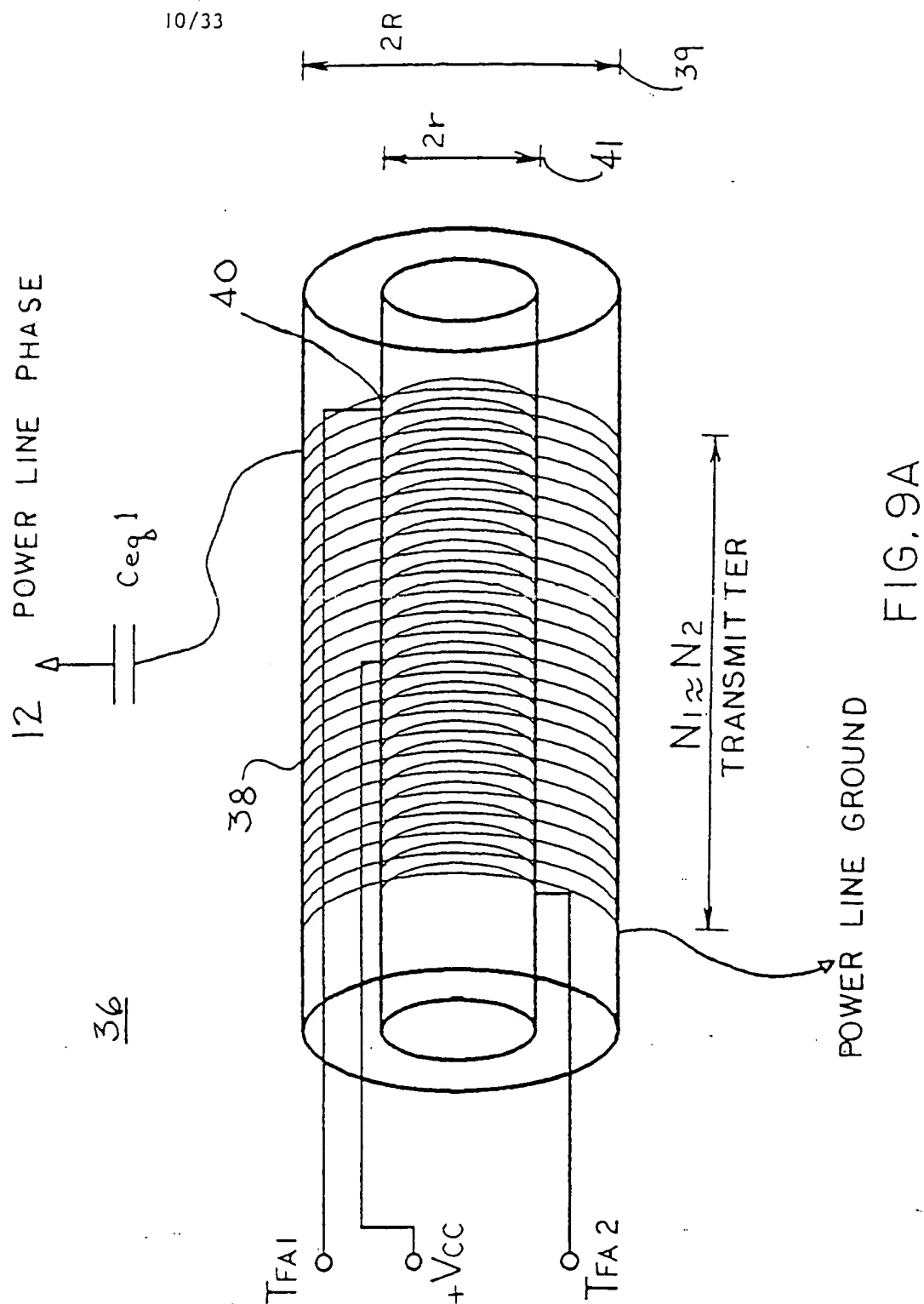


FIG. 8

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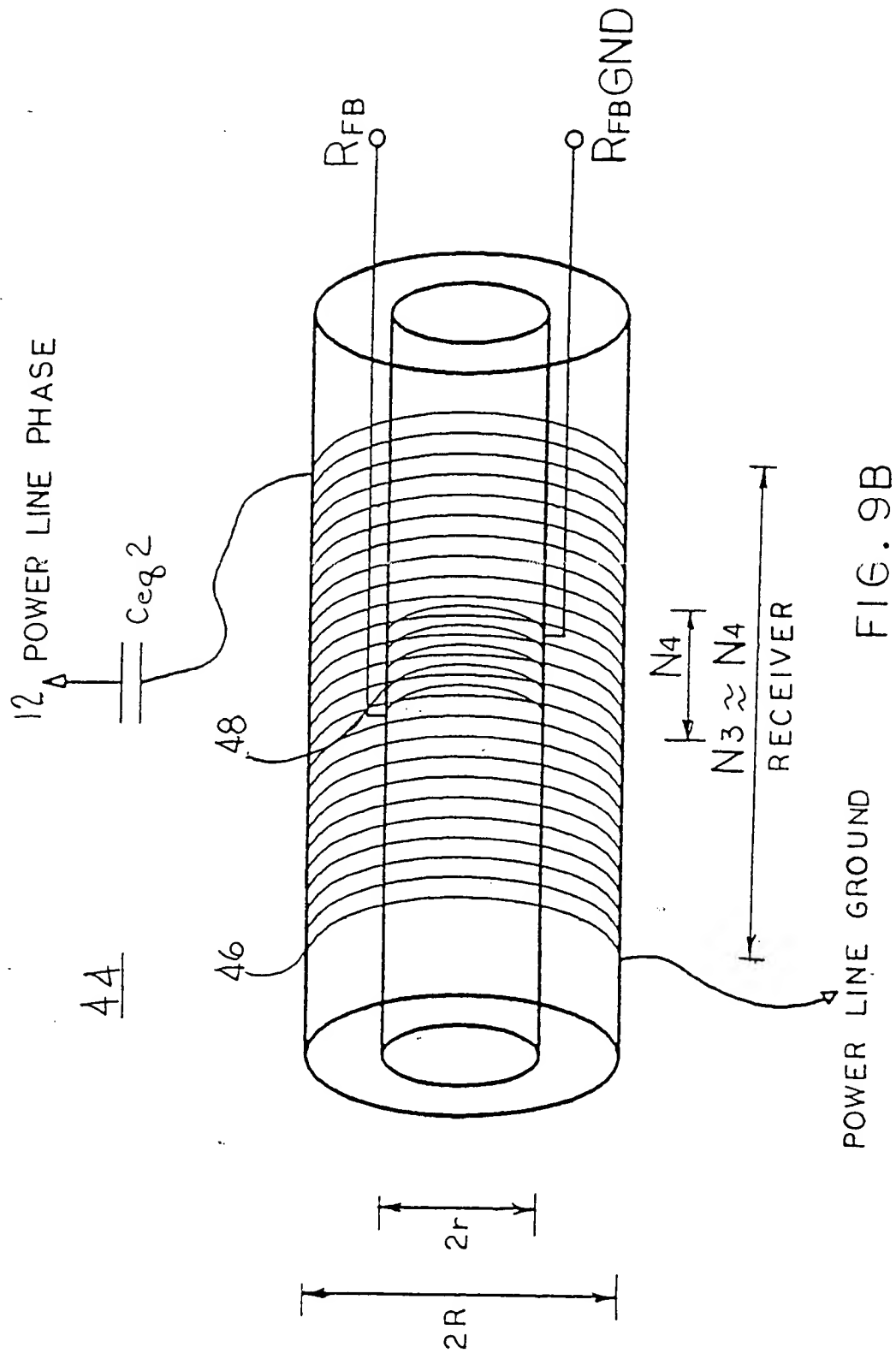


FIG. 9B

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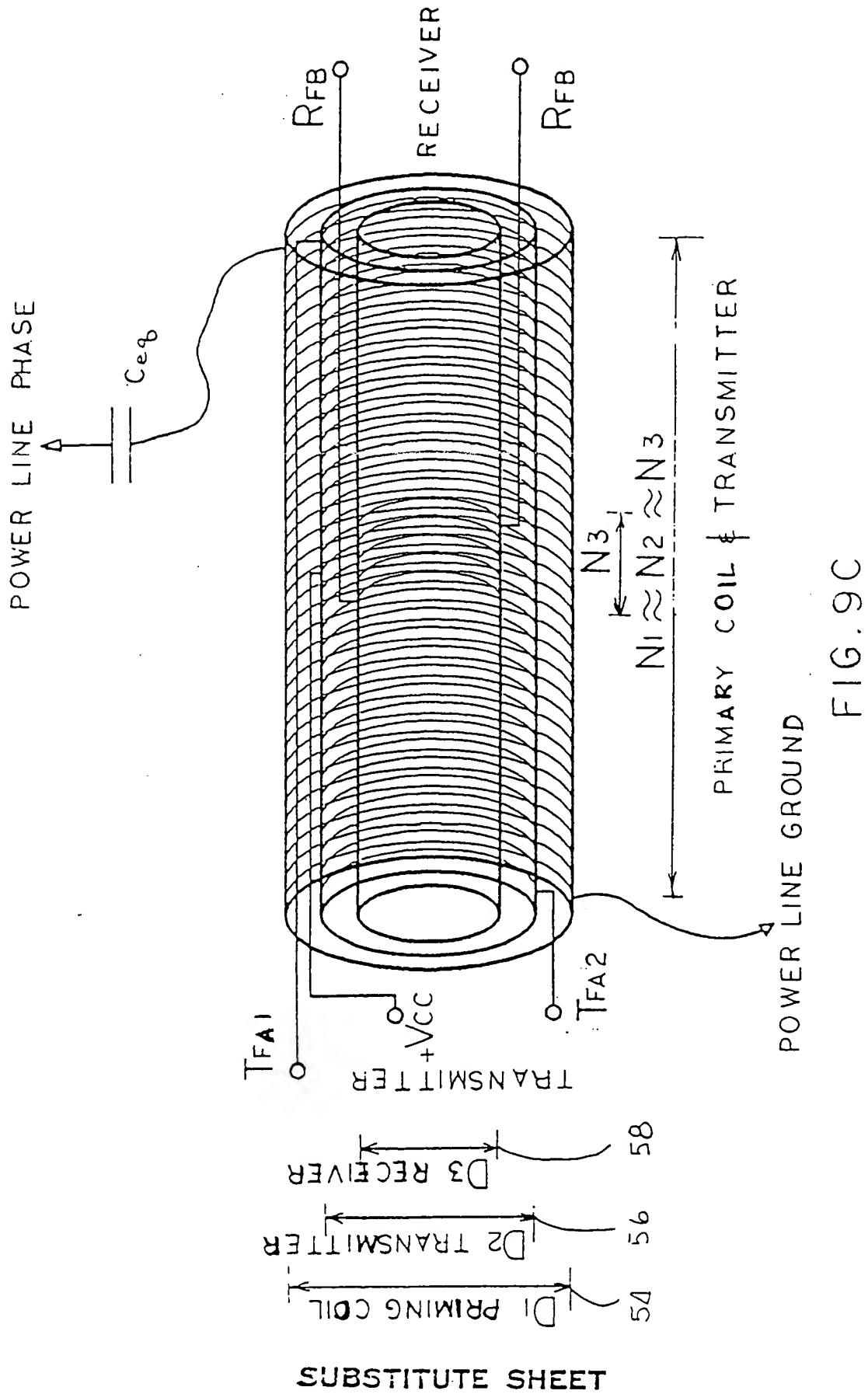


FIG. 9C

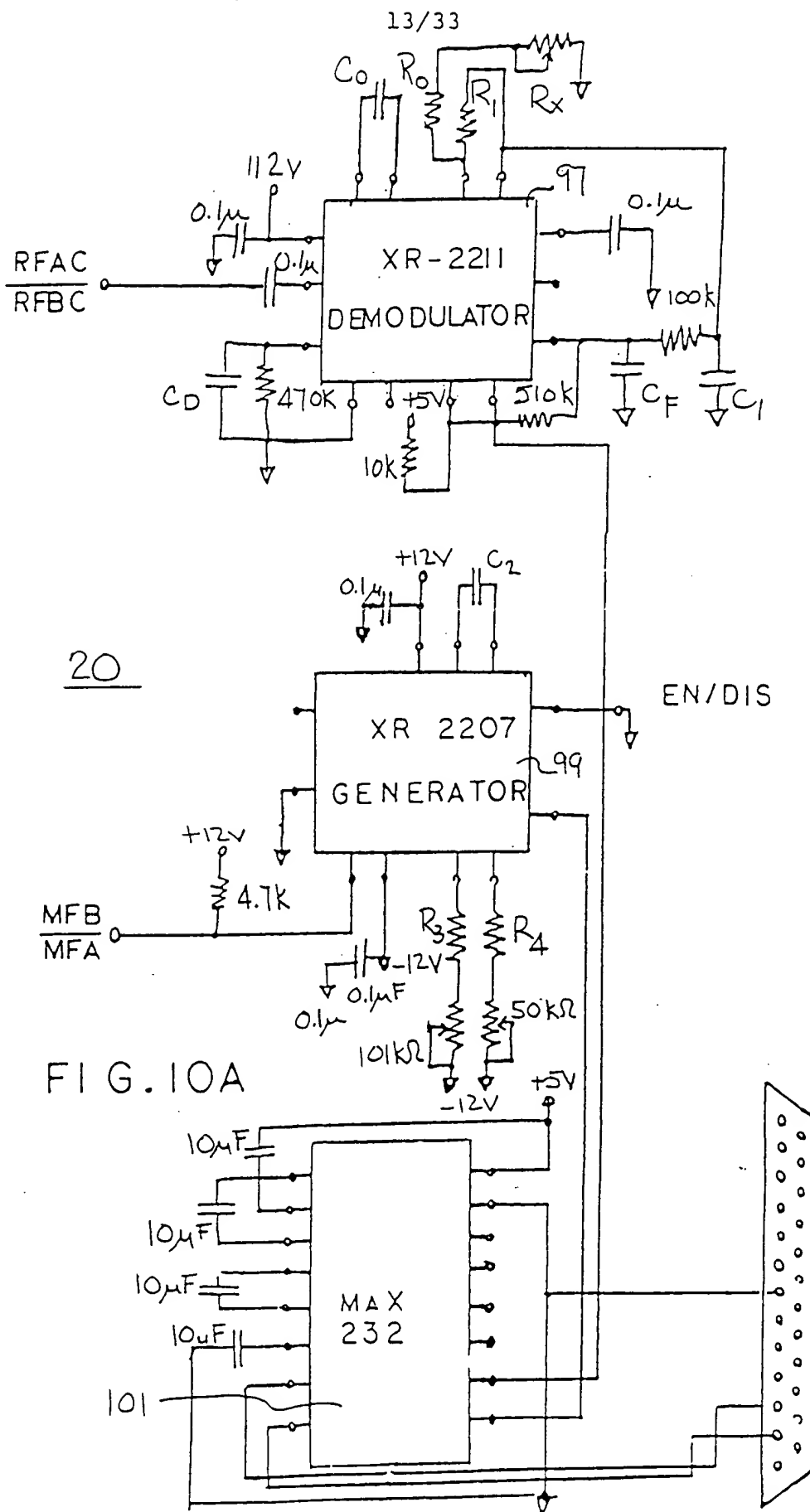
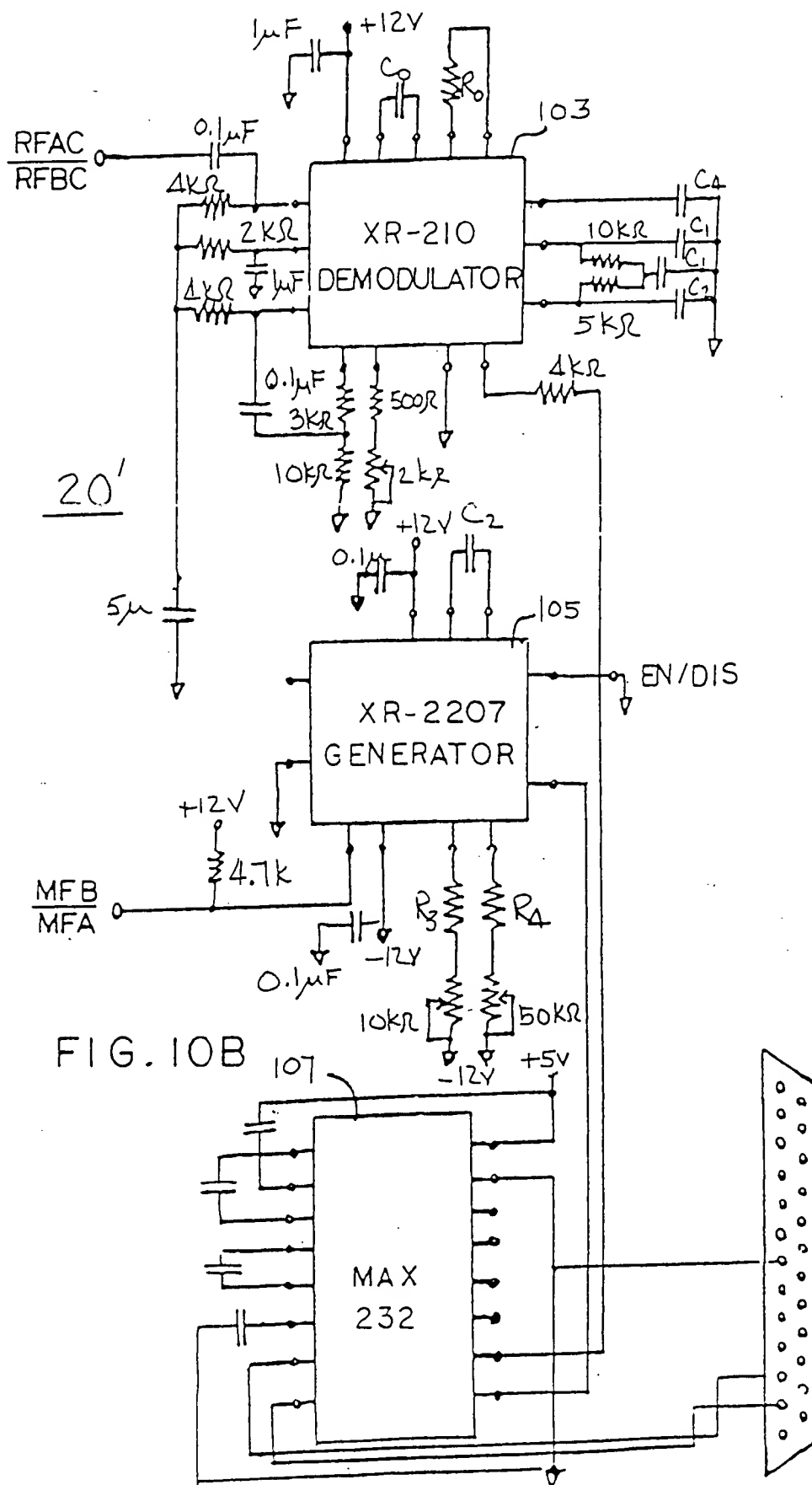


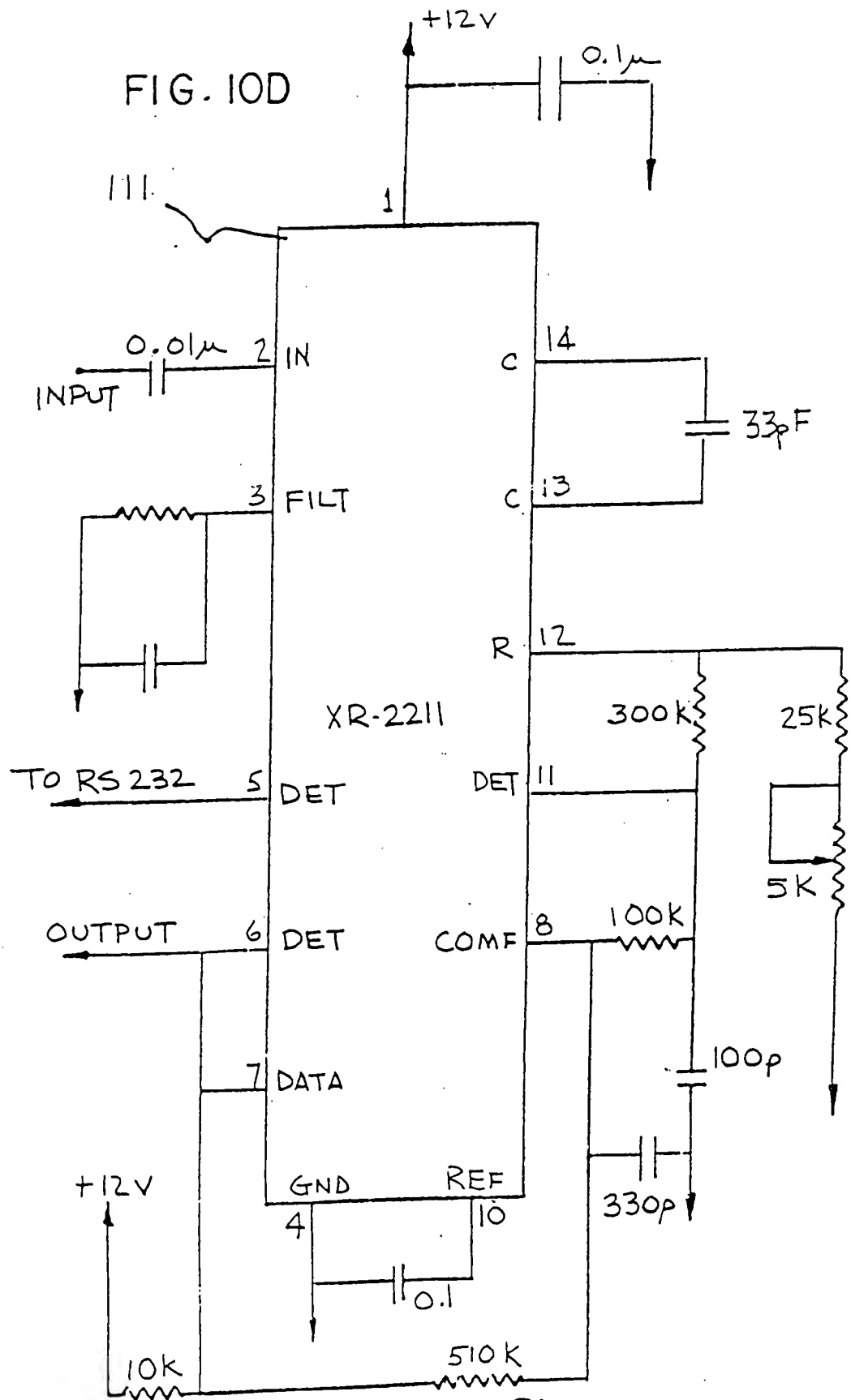
FIG. 10A

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FIG. 10D



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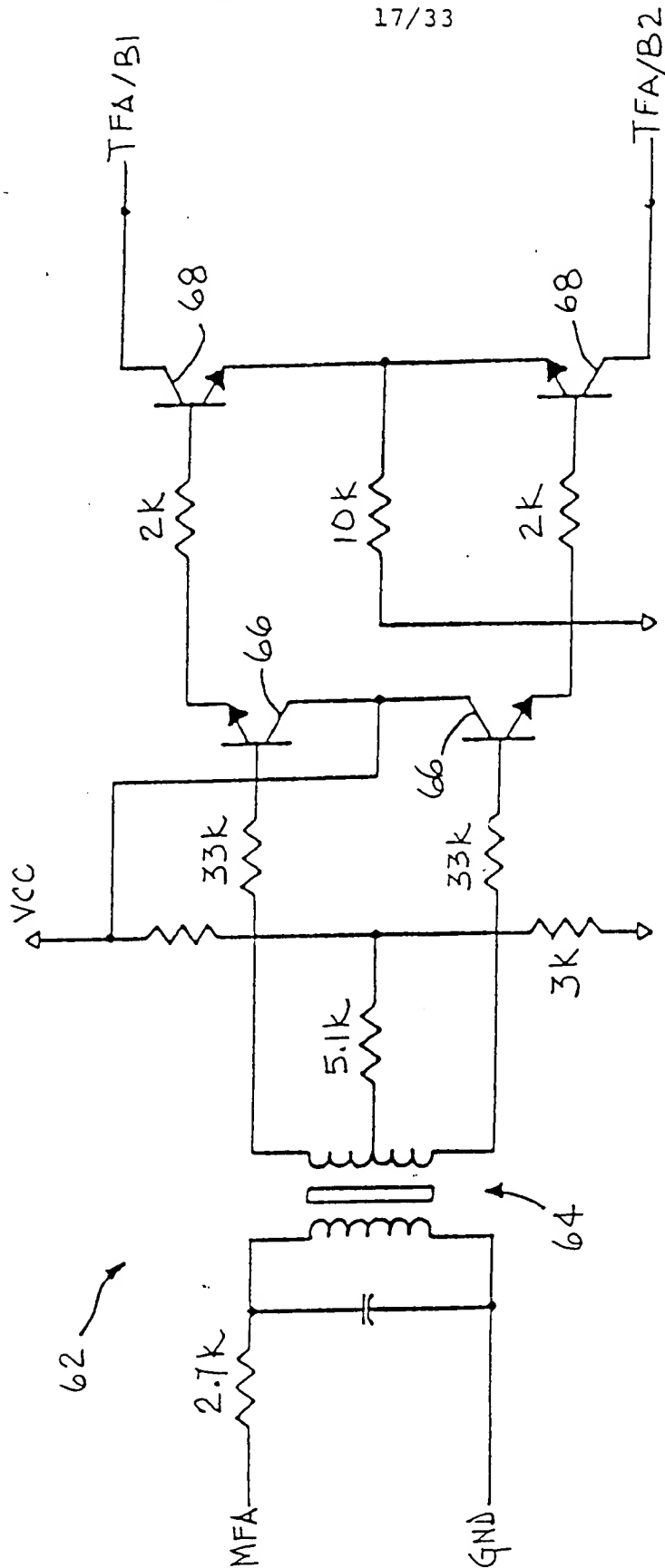
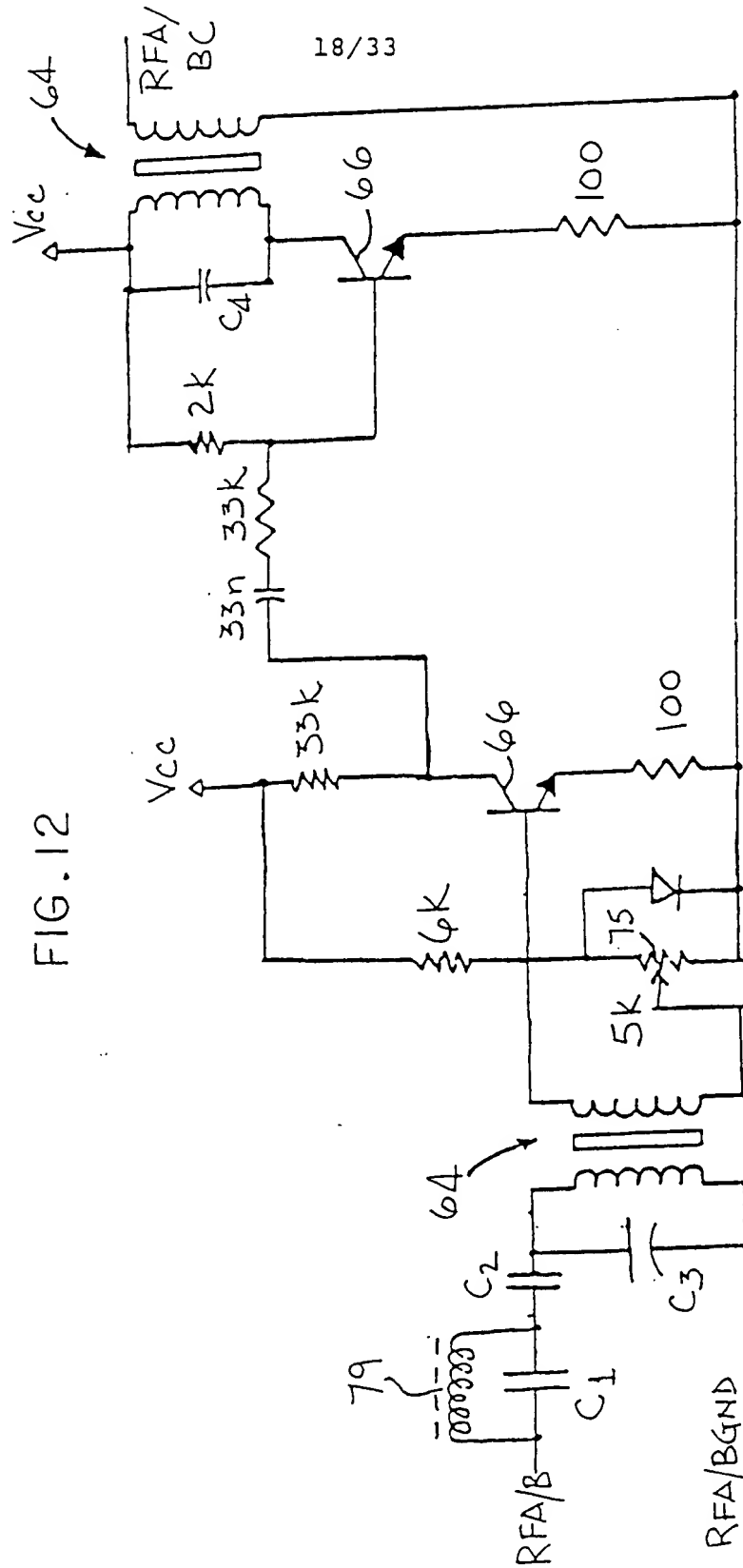


FIG. 11

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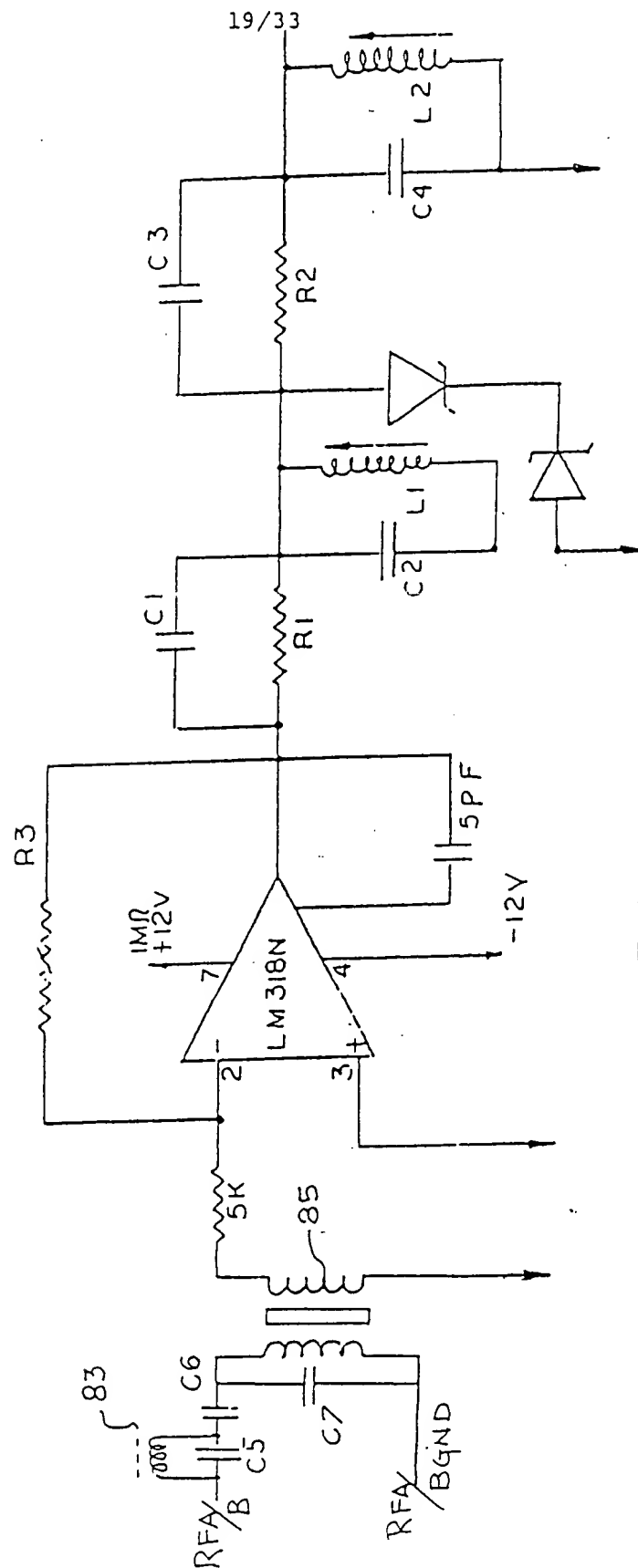
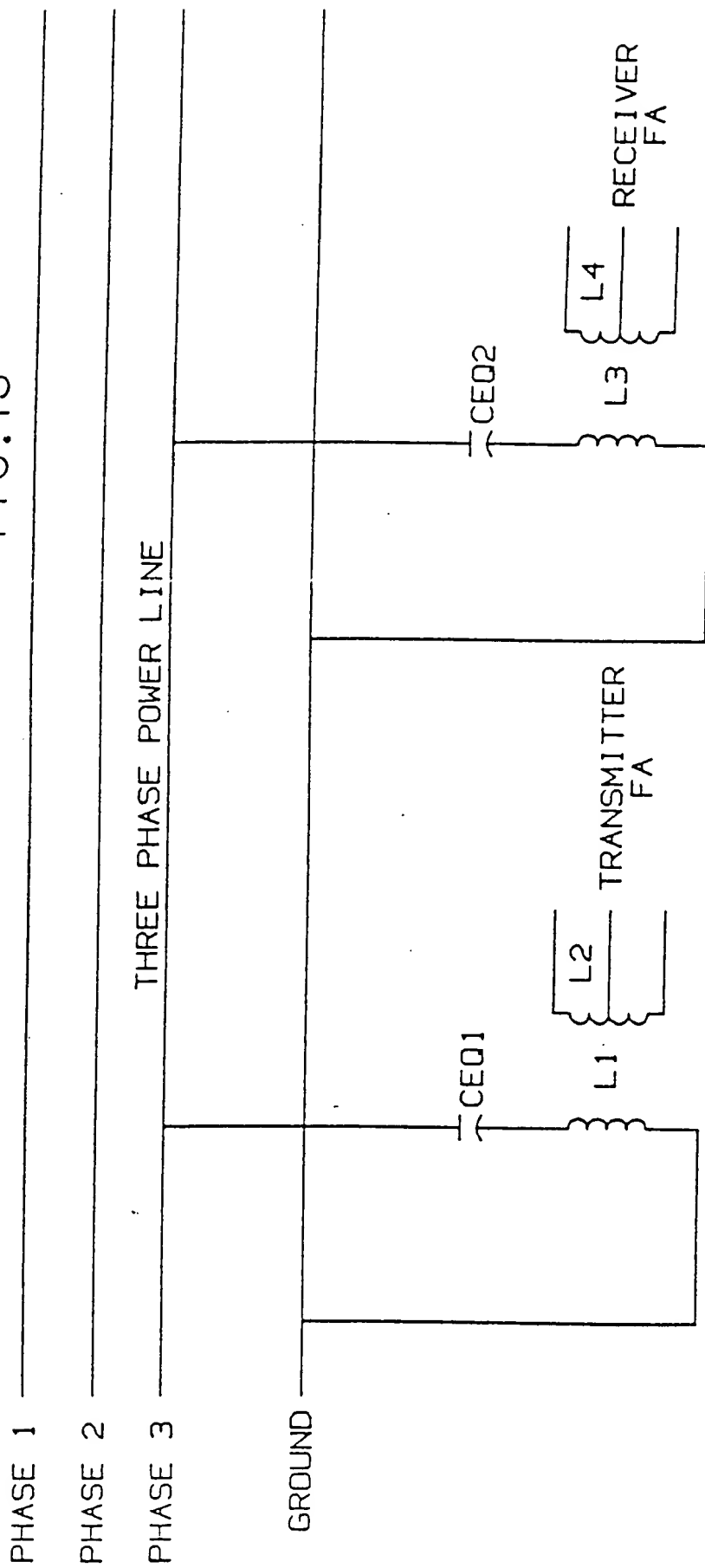


FIG. 12A

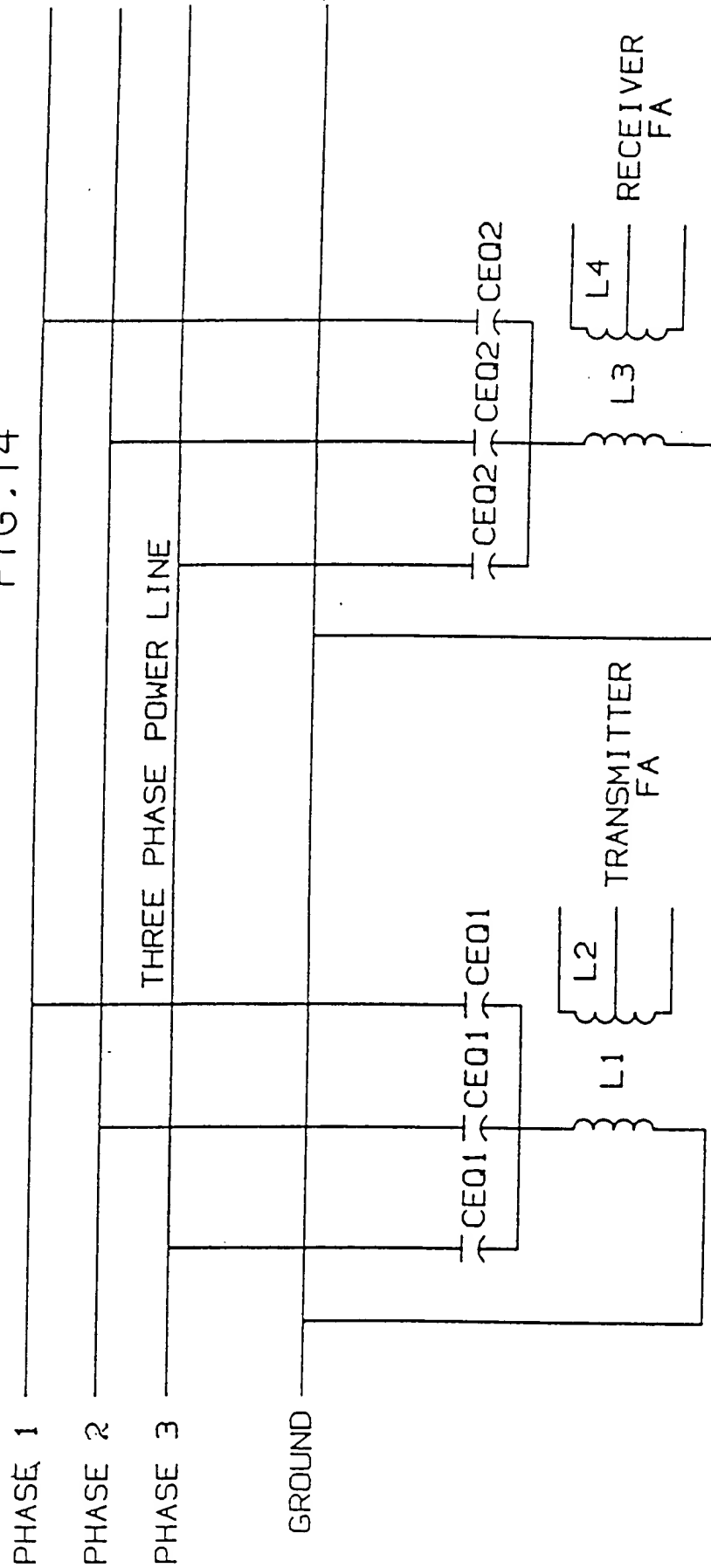
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FIG. 13



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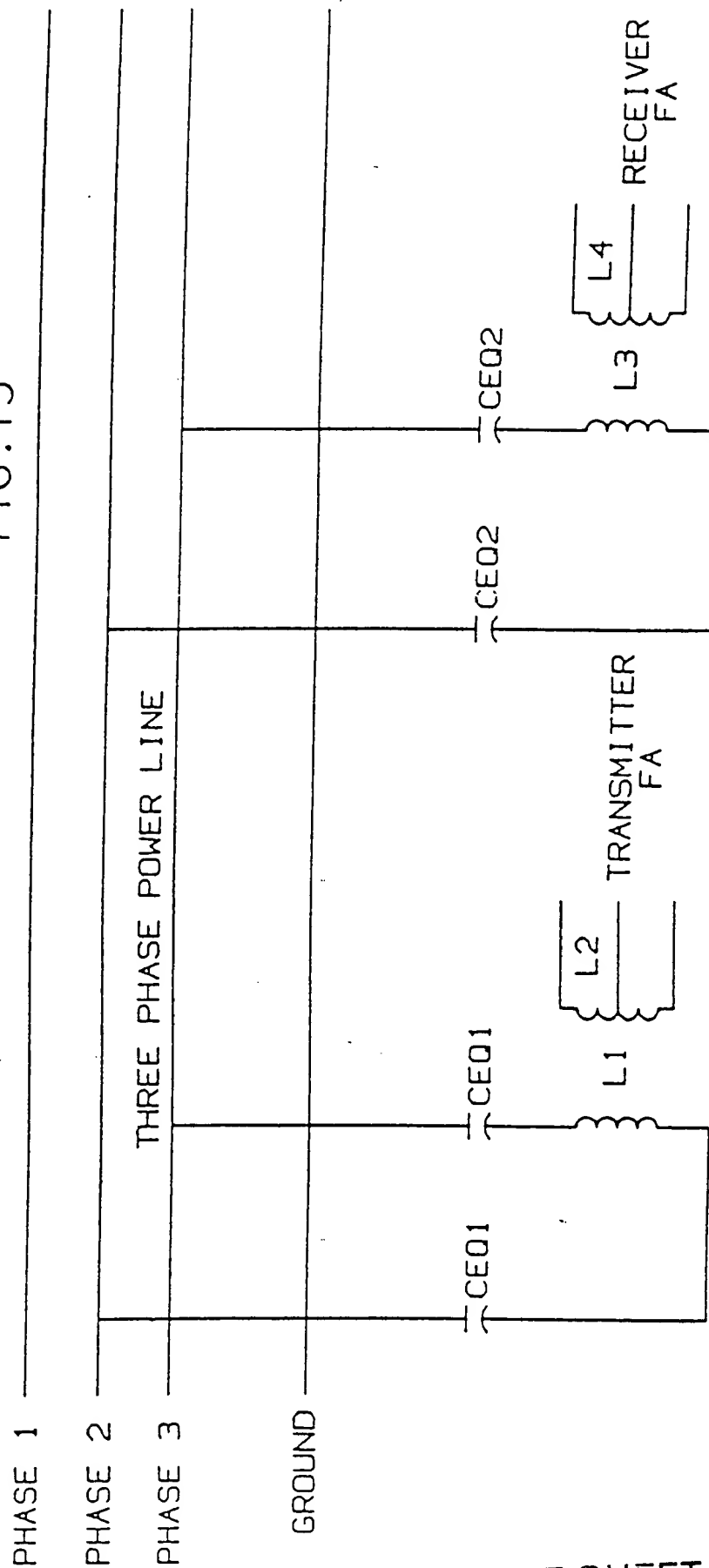
FIG. 14



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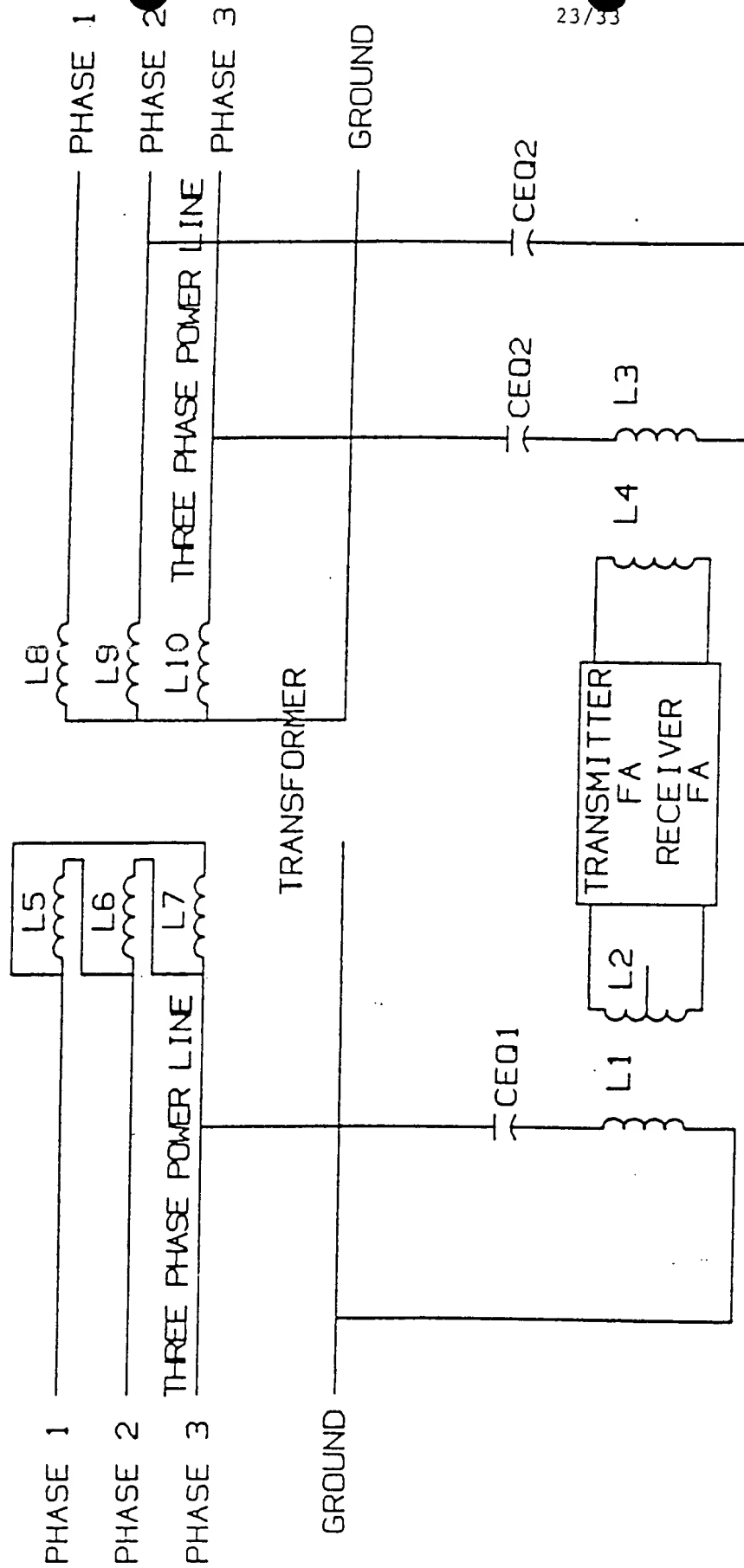
FIG. 15



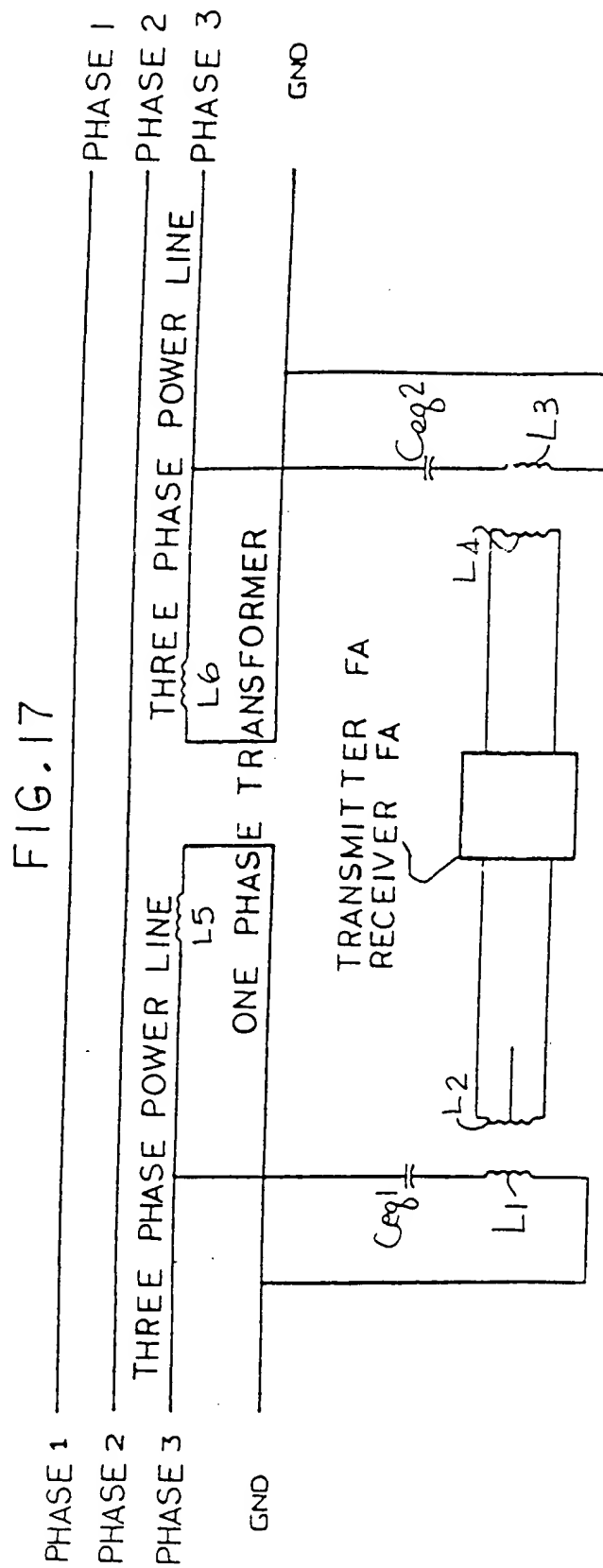
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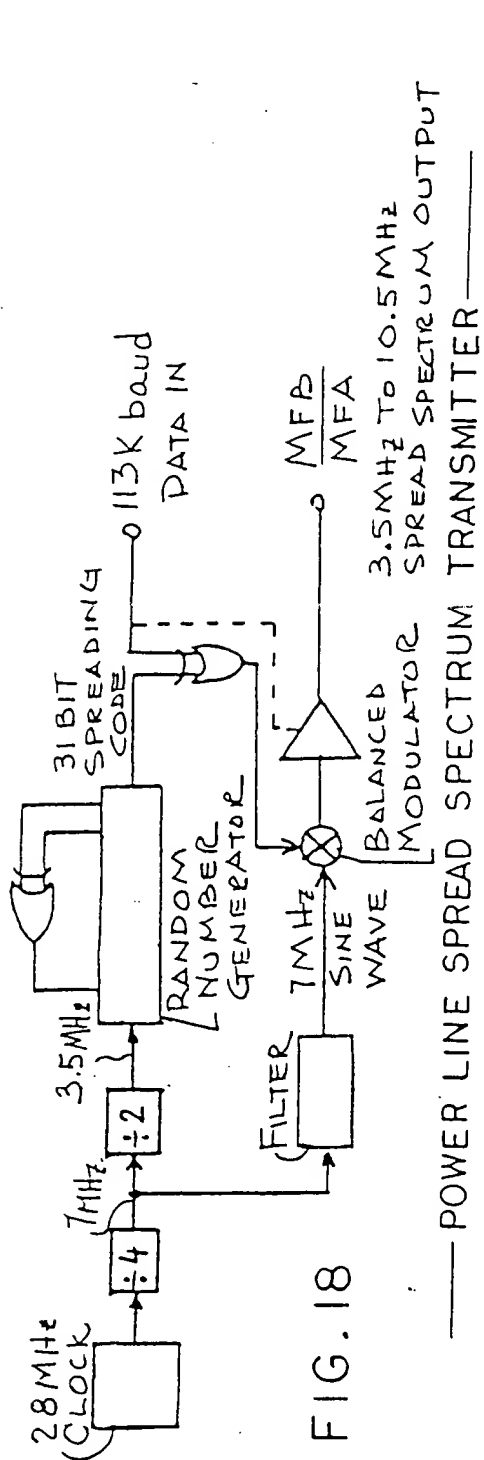
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FIG. 16



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— 6 —

— POWER LINE SPREAD SPECTRUM TRANSMITTER —

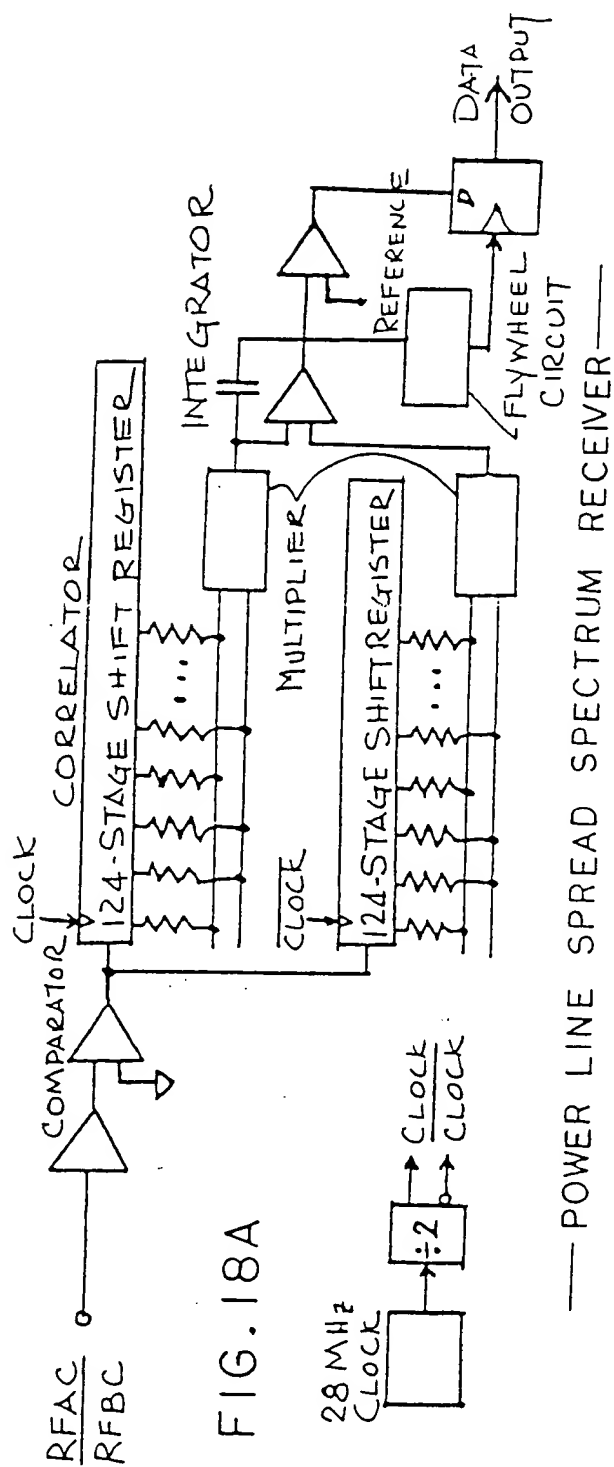
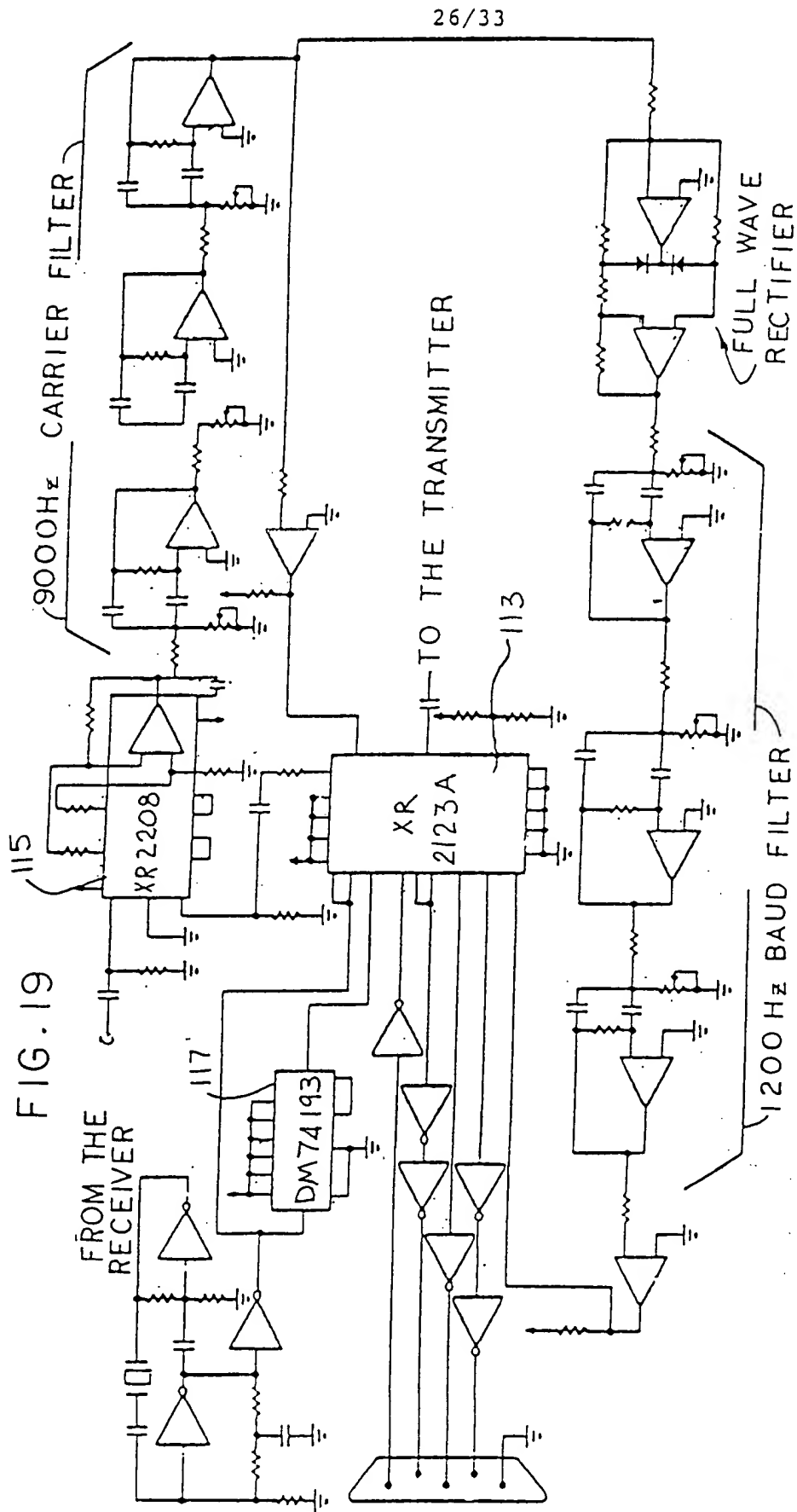


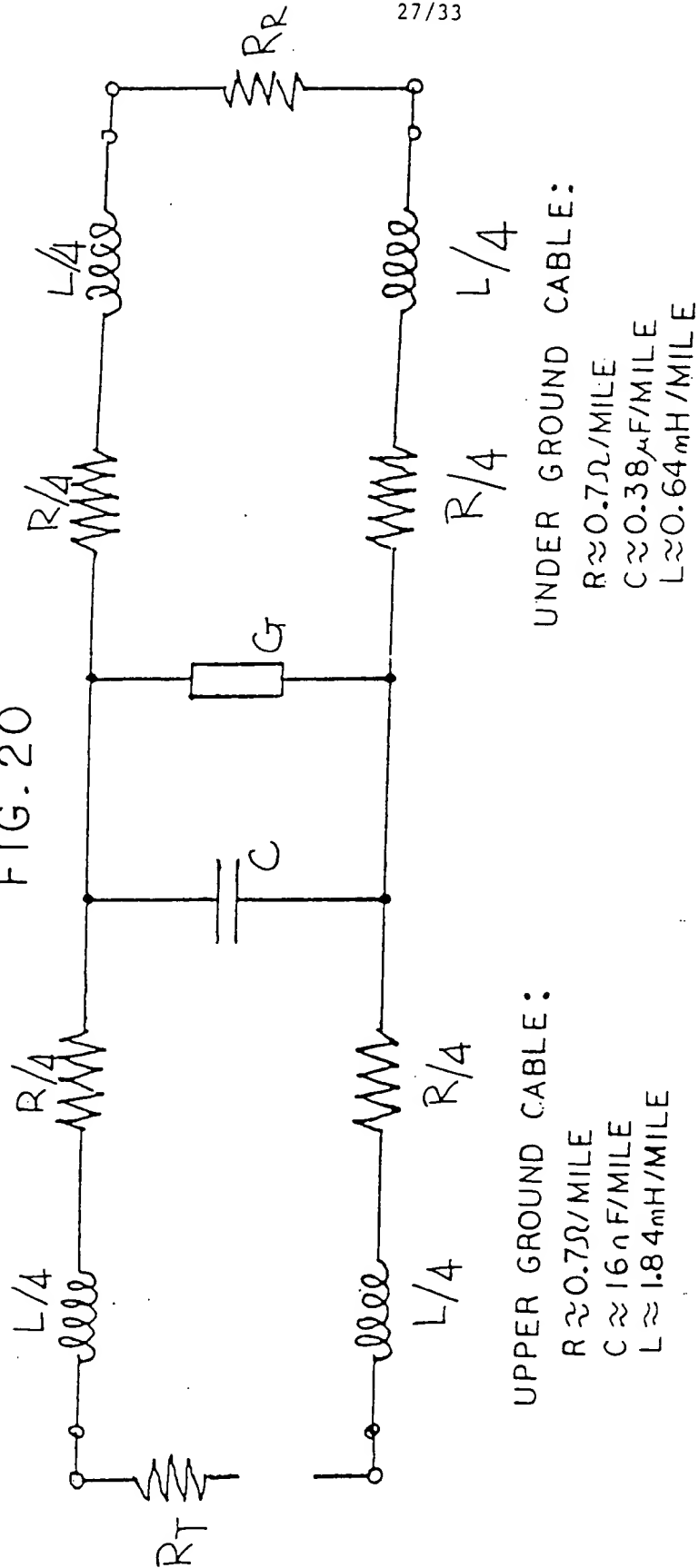
FIG. 18A

—POWER LINE SPREAD SPECTRUM RECEIVER—CIRCUIT



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FIG. 20



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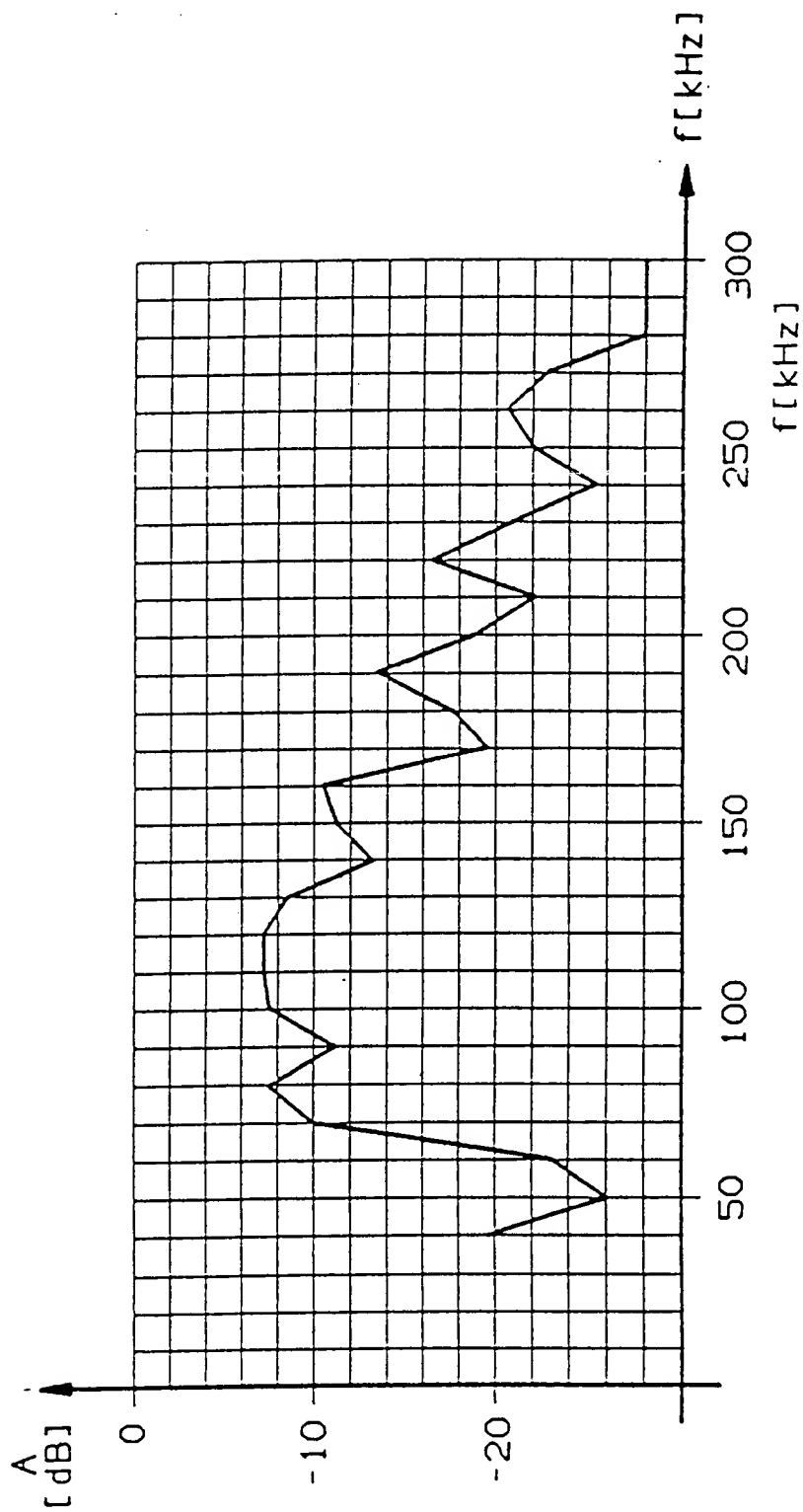


FIG. 21

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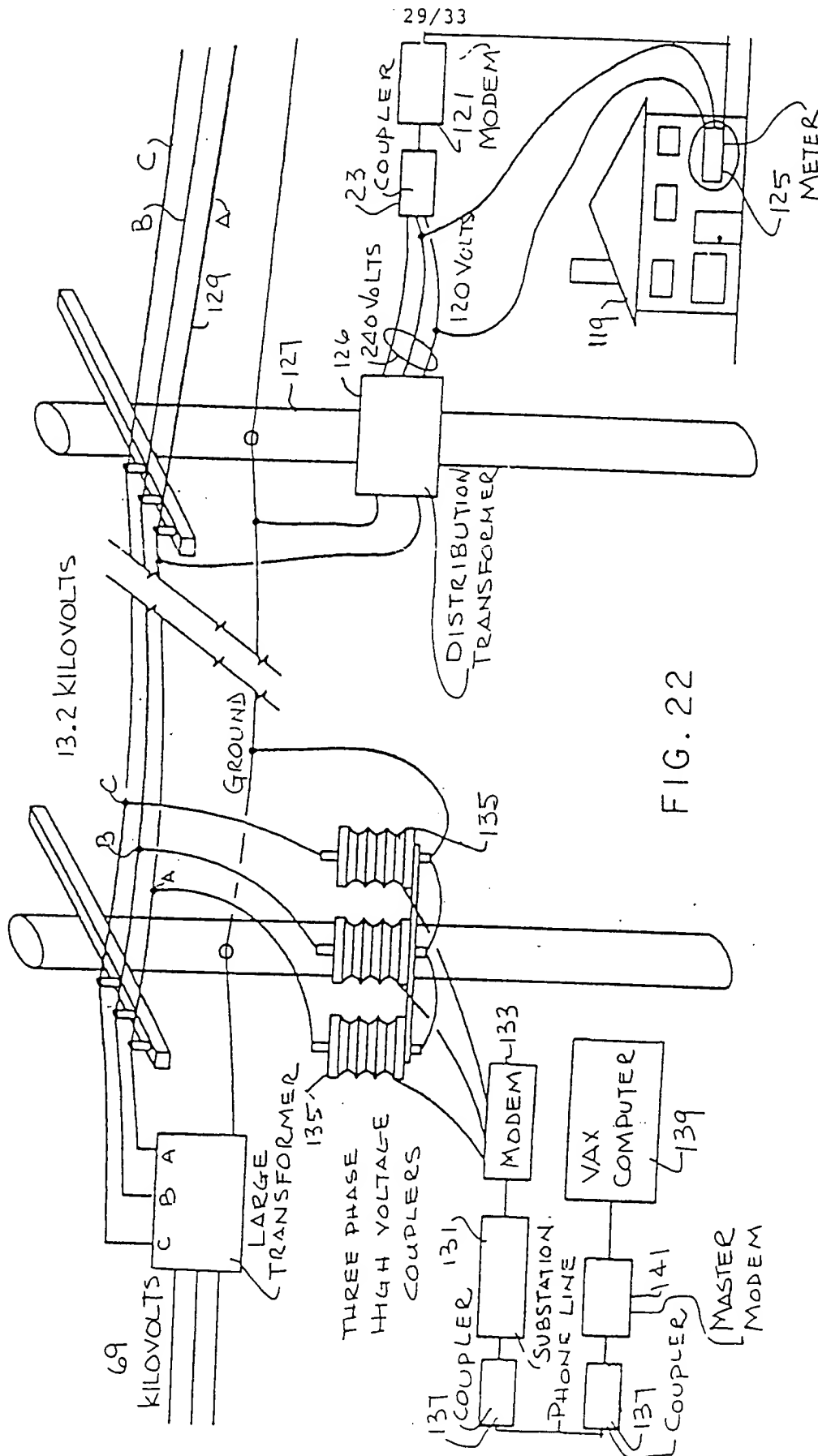


FIG. 22

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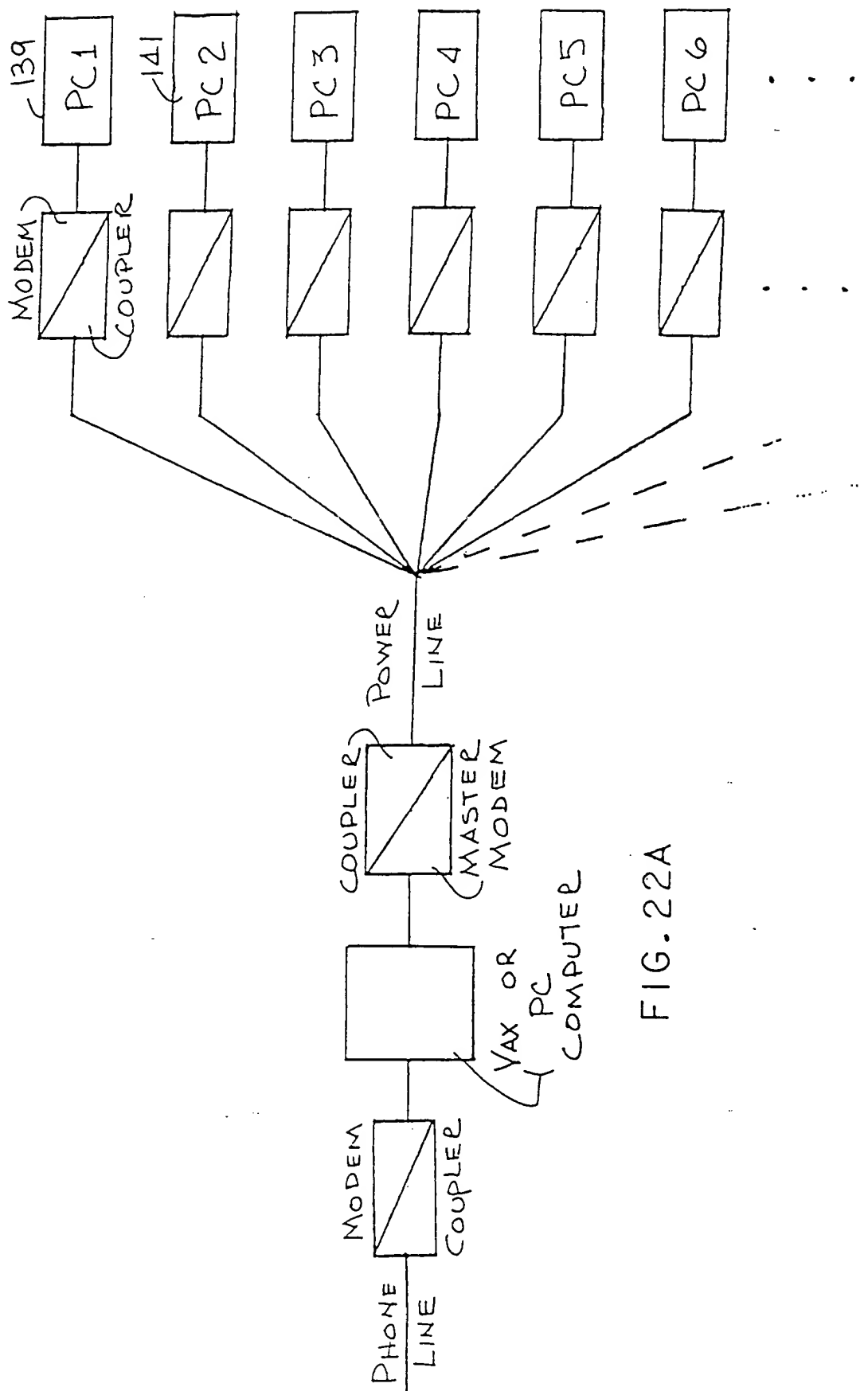


FIG. 22A

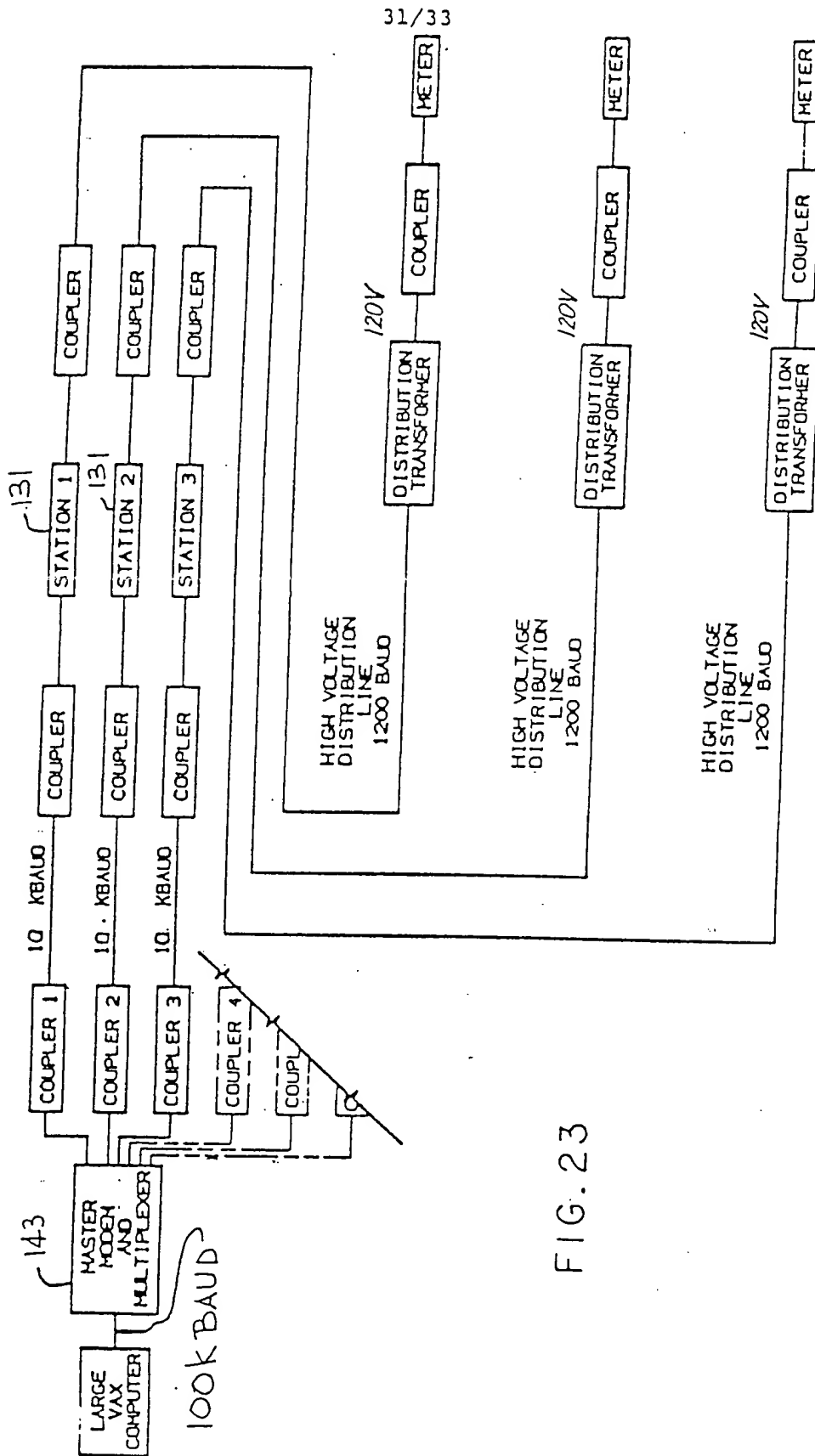
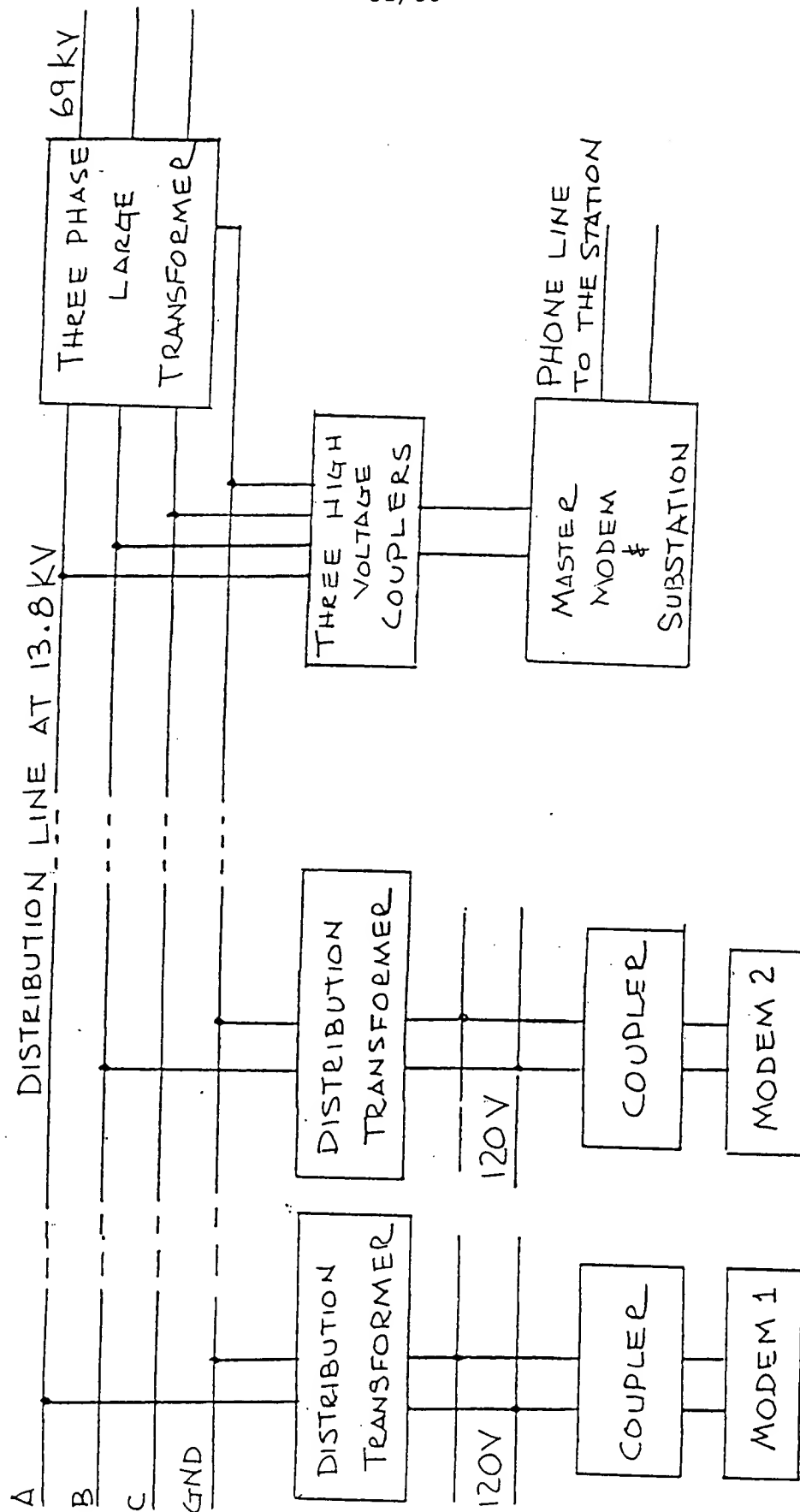


FIG 24



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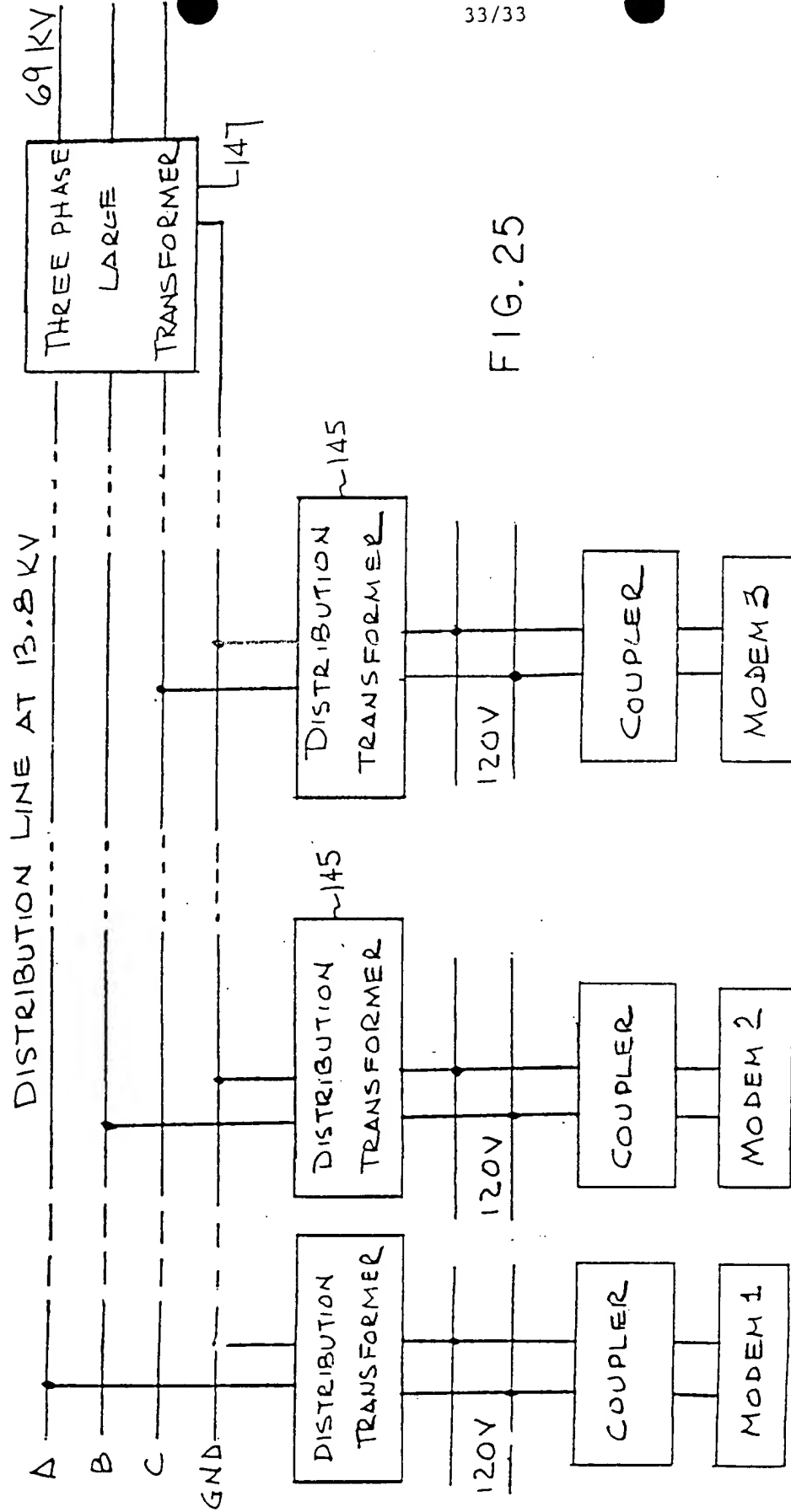


FIG. 25

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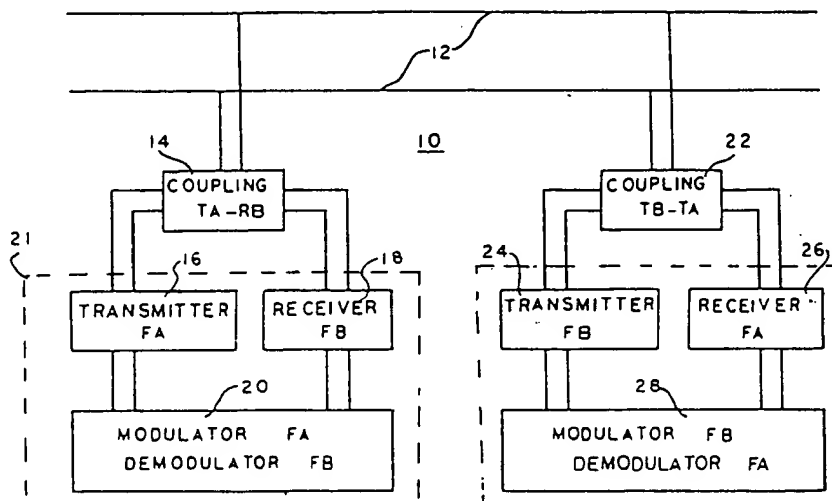
H04B3/56

UNDER THE PATENT COOPERATION TREATY (PCT)

- 1 -

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			(43) International Publication Date: 15 November 1990 (15.11.90)
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(54) Title: POWER-LINE COMMUNICATION APPARATUS



(57) Abstract

Apparatus for power system communications includes a coupler (14) at each of two or more locations along a pair of power-lines, the coupler having a pair of serial LC circuits with an air coil. A transmitter (FA), a receiver (FB), and a modem (20) is also provided at each of the locations such that each of the LC circuits of the couplers (14) resonate at a given frequency. The apparatus incorporate novel non-linear transformers which eliminate the signal from the power line and its harmonics, and which permit rapid transmission of signals for communications and other uses.

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INTERNATIONAL SEARCH REPORT

International Application No

PCT/US90/02291

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all) ³

According to International Patent Classification (IPC) or to both National Classification and IPC

IPC³ HO4B 1/50 HO4L 5/14

U.S.CL. 370/30 340/310R

II. FIELDS SEARCHED

Minimum Documentation Searched ⁴

Classification System

Classification Symbols

U.S.CL. 370/24, 27, 28, 30
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Category ⁶	Citation of Document, ¹⁵ with indication, where appropriate, of the relevant passages ¹⁷	Relevant to Claim No. ¹⁶
Y	US, A, 4,058,678 (DUNN ET AL) 15 November 1977 See col. 6, line 32 - col. 11, line 3.	1,3,8-11,13-15, 17,18,24
A	US, A, 4,885,563 (JOHNSON ET AL) 05 December 1989	

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IV. CERTIFICATION

Date of the Actual Completion of the International Search ²

17 OCTOBER 1990

International Searching Authority ¹

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Date of Mailing of this International Search Report ²

05 FEB 1991

Signature of Authorized Officer ²¹

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Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int. Cl.5)
A	EP-A-0 115 814 (SIEMENS AG.) * page 2, line 19 - page 3, line 36; figures * ---	1, 12, 14, 15	H04B1/50 H04L5/14
A	EP-A-0 156 557 (CONTROLONICS CORP.) * page 4, line 13 - line 26 * ---	1, 12, 14, 15, 23, 24	
A	PATENT ABSTRACTS OF JAPAN vol. 10, no. 283 (E-440)(2339) 26 September 1986 & JP-A-61 102 009 (TAKEISHI IKEDA) 20 May 1986 * abstract * -----	1, 14, 15, 29	
			TECHNICAL FIELDS SEARCHED (Int. Cl.5)
			H04B H01F
The supplementary search report has been drawn up for the claims attached hereto.			
Place of search THE HAGUE		Date of completion of the search 24 APRIL 1992	Examiner BOSSEN M.
<p>CATEGORY OF CITED DOCUMENTS</p> <p>X : particularly relevant if taken alone Y : particularly relevant if combined with another document of the same category A : technological background O : non-written disclosure P : intermediate document</p> <p>T : theory or principle underlying the invention E : earlier patent document, but published on, or after the filing date D : document cited in the application L : document cited for other reasons ----- & : member of the same patent family, corresponding document</p>			